SOILS AND FERTILIZERS

Frontispiece *Soil Conservation Service*

The handwriting of erosion. The first essential of good soil management is to keep the soil in place.

SOILS
and
FERTILIZERS

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PREFACE

The purpose of this book is primarily to acquaint the student with the applications of those scientific facts and principles that are of use in planning constructive systems of soil management and in increasing the productive capacities of soils. It is assumed that the student has had courses in chemistry, botany, geology, and physics and that he is familiar with the ordinary vocabularies of these sciences.

Many of the applications of the above sciences which are of interest to the more advanced student of soils are not touched upon in the following pages except in a very brief way. This is because the book is intended primarily for use in beginning courses in soils in agricultural colleges, in which many of the students are not interested in the more technical phases of the subject and have little or no need for the course except as it may be useful to them in practice or in understanding practice on the farm.

It is not deemed desirable to present any large part of the experimental data on which the author's conclusions are based. For this reason, illustrative material has been chosen from whatever sources were found to supply the most conclusive evidence. Similarly, it is not thought advisable to give an extended list of references; but at the end of each chapter there is a list of representative books, papers, and bulletins which will serve to give the student a fairly comprehensive idea of the nature of the research work that has been undertaken on the subject in question.

It is assumed that the classroom discussion of the subject will be supplemented with laboratory studies designed to fix more definitely in the students' minds some of the more important facts and principles which lend themselves to laboratory demonstration.

It is hoped that this book may also prove useful to those who are not in college but who, by experience or training, are in a position to follow the discussions and to profit from a modern statement of the problems of soil management and of methods for their solution.

This book has been thoroughly revised for the third edition, and some additional concepts have been introduced. The author is especially indebted to Dr. Stephen J. Toth, a colleague at the New Jersey Agricultural Experiment Station, for assistance in this connection. He also wishes to express his appreciation to Miss Ruth Bochert for aid

in the preparation of the revised manuscript and in the reading of the proof.

The name of the book has been changed from "Soil Management" to "Soils and Fertilizers." This change was decided upon because of the ever-increasing importance of lime and fertilizer materials as aids in maintaining and increasing the productivity of soils and because the book deals, in considerable part, with these materials and their uses.

FIRMAN E. BEAR

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FOREWORD

Soil is practically indestructible. It consists mostly of rock residues that have survived the rain, wind, heat, and frost of the centuries. In humid areas, all but mere traces of any soluble substances which these rocks could be made to yield up have long since been washed into the sea. The insoluble part — the soil — remains as an enduring foundation on which civilizations are built and rebuilt.

Soil constantly seeks lower levels and, like the soluble salts that have been washed out of it, may finally find its way into the sea. Much of the soil which now covers this continent had once been on the ocean floor, where it was reconsolidated into limestone, sandstone, or shale. Centuries later, it was re-elevated and remade into soil — often several times over.

For thousands of years before the Americas were discovered, the soil of this hemisphere was sewed to the earth by the roots of trees and grass. But the early pioneers cut down the forests and tore up the sod, and the soil started down hill. It has been moving down hill ever since. More quickly than have those of any other nation or of any other time, the farmers of the United States plowed their way down into the subsoil. One of the most significant developments of recent times, however, has been the rapidly growing realization that we plow too much.

It will be recalled that corn, tobacco, and potatoes were unknown in the Old World, and that our European ancestors had no firsthand knowledge of these crops or of cotton. Our inherited experience had not taught us how to cope with their soil-denuding powers. About 140 million acres of our best land were being plowed up and planted to these clean-cultivated crops annually before anyone realized what a disastrous effect they were having on the staying powers of the soil. Once this was clearly understood, immediate steps were taken to apply correctives. Many modern farmers now avoid plowing their land whenever possible. In Missouri, for example, large acreages of corn have been replaced by winter barley, wheat, and rye. Farmers grow these small grains year after year without plowing the land. The soil is merely redisced each fall, and reseeded to the small grain. Lespedeza, sown in the grain, collects the necessary nitrogen from the air, and provides profitable grazing for livestock.

In Nebraska, the natural mulch of crop refuse is now being allowed to remain on the surface of the land as a protective measure against loss of soil by wind and water erosion. Seed are planted under this mulch and allowed to grow up through it. Thus, the soil is never turned upside down, but such working of it as is required is accomplished by the use of a duckfoot cultivator.

In New Jersey, the grassland system of farming, in which grasses and legumes are substituted for corn as silage crops, bids fair to revolutionize soil-management systems on dairy farms. This does not mean that corn is to be entirely eliminated, but that it will be confined to land which is so level, either naturally or by contour farming, that little loss of soil from surface erosion occurs while this crop is being grown.

If a fertile soil can be kept in place, the problem of keeping the soil fertile is a relatively simple one. Crop nutrients consist of elements which tend to escape into the ocean and the air and which must be brought back to the land as required. The needed limestone, phosphate, and potash are obtained from ancient seas which are now dry land. The necessary nitrogen is captured from the air in enormous nitrogen-fixing factories that, for military as well as agricultural reasons, are widely scattered over the earth. Our lime and fertilizer bill amounts to over 2 hundred million dollars annually.

But lime and fertilizer alone do not meet the requirements in building up poor soils. One cannot substitute chemicals for sod and its soil-improving effects. If the farmer applies his lime and fertilizer and goes ahead with the same plowing and clean-cultivation procedures, the soil will still move down hill. And the longer this process is continued, the faster this movement takes place. It finally reaches a point where we are constantly faced with the necessity of making new soil out of subsoil — an expensive procedure.

More consideration is now being given to the development of soil-management systems in which there is a judicious mixing of soil-resting crops and clean-cultivated crops, when the clean-cultivated crops must be grown. And when we rest the land, we now put more thought into just how we can make the most of the period during which the soil is being kept out of the production of money crops. The answer lies in the growing of some type of sod-forming crop and in the feeding of this crop so well that it can develop both a good root and a good top. The sod crop must be made to produce its maximum effect on the soil, both while it is being grown and after it has been plowed under.

The problem of soil management resolves itself largely into a planned program designed first, to keep the soil in place; and, second, if the land must be plowed, to have it so well stocked with organic matter that it will suffer little loss from the action of wind and water. Sooner or later we have to pay the price for mismanagement of the soil. At first, this may mean an unprofitable agriculture on only an occasional farm. In time, it may mean a decadent agriculture over a whole county, state, or nation.

F. E. B.

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CHAPTER I

FACTORS AFFECTING CROP GROWTH

The factors affecting the growth of crops may be conveniently classified into three groups, namely: climatic, biotic, and edaphic. The most important climatic factors are precipitation, sunshine, and temperature. Under the biotic group may be listed man, animals, other plants, and the crop itself in relation to its environment. The edaphic group comprises all those physical, chemical, and biological properties of the soil and processes in the soil that affect its capacity to supply the crop with the necessary nitrogen, mineral nutrients, and water.

Each of these factors may affect the crop either positively or negatively, depending upon the conditions which obtain. They are all interrelated in their effects. It is seldom, if ever, possible to have all of them operating at the optimum at the same time. The success of the farmer in growing crops is determined by the extent to which he is able to keep the several factors affecting them under control; to modify the effects of these factors to meet the needs of his crops; and to choose the crops that are best adapted to the conditions with which he has to deal.

CLIMATIC FACTORS AND CROP GROWTH

The climatic factors are so related to each other in their effects on crop growth as to make it very difficult to consider them separately. The water supply of plants is not so much dependent upon the amount of rainfall as it is upon the rainfall-evaporation ratio: under some conditions the atmosphere offers serious competition to the crop for water. Certain crops grow best in cool climates, but this may be due as much to the more abundant water supply under those conditions as to the direct effect of the temperature. The photosynthetic processes in plants are dependent upon the light, but the intensity of the sunshine is ordinarily much in excess of their requirements: length of day and of the crop season are the important phases of the light factor.

There is a relationship between the length of day and the flowering and fruiting of plants. This becomes apparent when one attempts to grow plants at latitudes far removed from those to which they are accustomed. Some plants do not bloom unless the days are relatively long; others bloom only when the days are short; and others will bloom no matter what the length of the day. Blooming is only an index of other more deep-seated phenomena that are governed by the light

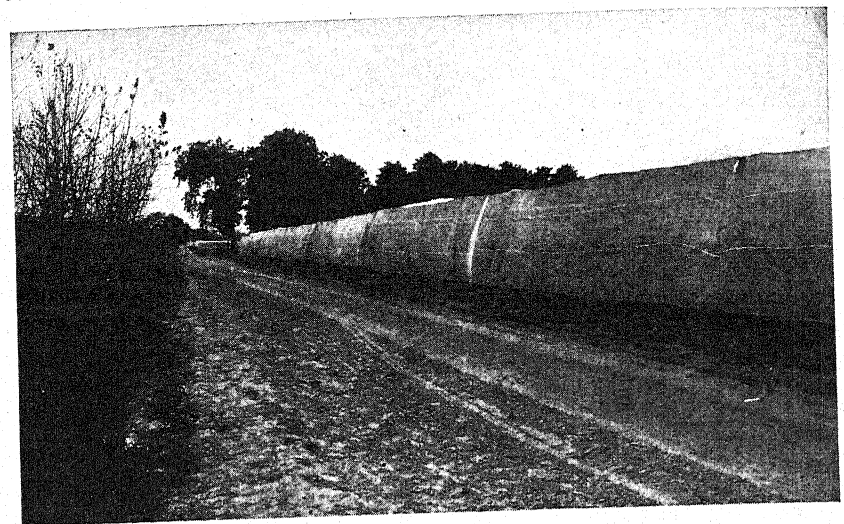

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FIG. 1. Outside view of field under canvas used to control climatic factors. This method is effective in improving the quality of certain types of tobacco.

factor. It is a well-known fact that the farther north the locality, the longer the long days and the shorter the short days of the year. At the Canadian border the longest days are two hours longer and the shortest days two hours shorter than the corresponding days at the Gulf coast. Furthermore, the twilight and the dawn are longer in northern latitudes.

In these light relationships are to be found, at least in part, the explanation of the differences in the yield of crops, depending upon the latitude in which they are grown. It is well to keep this fact in mind in connection with the discussion on the relation between climatic factors and crop distribution, since it may later be shown that length of day is the controlling factor where other climatic factors are now given the credit. Herein may lie the partial explanation of the 15 per cent average sugar content of Michigan beets, the 275 bushels an acre average yield of Maine potatoes, and the 42 pounds a bushel weight of Scotland oats, in comparison with lower percentages, yields, and weights, respectively, of these same crops in areas farther south.

It is not feasible to discuss in detail the relationships that exist between climatic factors and crop growth and distribution, but some of the more important cases will be considered. It seems desirable to note that the farther removed an area is from the climatic center of production of any crop, the more difficult it is for farmers to grow that crop satisfactorily, until a point is finally reached at which it may

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FIG. 2. Inside view of field shown in Fig. 1.

no longer be advisable to make the attempt. On the other hand, economic factors enter into this problem and often allow large expenditures for the control or the modification of the effects of climatic factors in localities far removed from the natural center of production of a given crop. Thus in greenhouse culture it has been found possible, and sometimes profitable, not only to control the moisture and temperature but also to lengthen or shorten the day by artificial means and to regulate the supply of carbon dioxide in the atmosphere.

CLIMATIC FACTORS AND CROP DISTRIBUTION

Although corn is grown under a wide range of climatic conditions, the most favorable environment for the crop is to be found in a relatively restricted area. The Corn Belt comprises that region in which the mean summer temperature is between 70° and 80° F., and the night temperature averages approximately 60°; in which there is a period between frosts of more than 140 days; and where the annual precipitation is from 25 to 50 inches, of which at least 7 inches should occur during July and August. The center of the Corn Belt comprises the states of Iowa, Nebraska, Kansas, Missouri, Illinois, Indiana, and Ohio. These seven states produce over half the corn grown in this country. It is of interest to note that most of the sweet corn is produced north of Mason and Dixon's Line.

The winter wheat crop thrives best in those areas where the climate is cool and moist during the autumn, winter, and early spring months and then gradually develops into a warm, bright, and somewhat dry harvest period. The areas of highest acre yields of winter wheat include England, Scotland, Belgium, the Netherlands, Denmark, northern France, and Germany. In the United States the most important center of winter wheat production is Kansas, extending into Nebraska and Oklahoma. Other heavy winter wheat-producing states are Washington, Missouri, Illinois, Indiana, Ohio, Pennsylvania, and Maryland. Low yields may usually be credited to one of four causes, namely: heaving, smothering, low temperatures, or drought. North of the mean winter temperature line of 20° F. the climate is better suited to spring wheat, of which the center of production is the Dakotas and Minnesota.

It is apparent that a good winter wheat climate is not the same as that described for corn. Nevertheless, these crops are grown successfully in rotation because wheat is essentially a winter and spring crop while corn does its growing in the summer months. The two crop seasons overlap somewhat and, for that reason, the best wheat-producing areas are often not entirely satisfactory for corn. Spring wheat cannot be grown to advantage in the Corn Belt because summer is too far advanced before the crop comes to maturity.

The same principle is involved with oats. This crop also is adapted to cool, moist climates and is much more seriously affected by high temperatures than is wheat. Not only are the acre yields much lower in southern latitudes, but the weight per bushel is considerably less. In Europe, the center of production of the oats crop is practically identical with that in which the highest acre yields of winter wheat are produced, although oats is grown as far north as the Arctic Circle. The most important oats-producing area of the United States extends from the Dakotas across the northern portion of the Corn Belt to western Pennsylvania and New York. Oats can be grown successfully in warmer latitudes only when it can be sown in the autumn and can have its growing season largely during the winter and spring months. Selection for cold resistance has made it possible to grow winter oats north of its former limit in southern Tennessee. Barley is another short-season crop that can be grown in high altitudes where the summers are short, and in semi-arid regions where the wet seasons last only a few weeks.

Potatoes also grow best in moist, cool climates, somewhat north of the Corn Belt in the United States, and in the area of high acre yields of wheat and oats in Europe. Both the quality and yield of tubers are better in regions of cool climate. Many of the centers of production of potatoes are not in areas in which the climate is ideal but in those that are close to large cities, where the saving in freight and in shipping risks serves to offset the disadvantages of lower yields. In the southern states, early potatoes are planted in November and December and harvesting begins about the middle of March. North of the latitude of New York City, most of the potatoes are late and are dug between the middle of September and the last of October. The production of sweet potatoes is largely limited to that area in which the growing season is over 175 days and the mean summer temperature is above 72° F.

The sugar beet is another crop that grows best and develops its highest content of sugar in areas of cool, moist climates. Its southern limit is at a summer temperature of about 72° F. Like oats and potatoes, sugar beets can be grown successfully in warmer latitudes if they are planted in the fall and harvested before the warm summer weather begins. On the other hand, sugar cane grows best under conditions in which the temperature is uniformly high, the sunlight is strong, and the showers are frequent. Cool and cloudy weather during the growing season reduces the yield of cane and increases the percentage of fiber. Later in the season, sugar cane requires either a lowered temperature or a lessened water supply in order to develop a high sucrose content. Colorado, California, and Michigan are centers of sugar beet production, and Louisiana of sugar cane, in this country.

Cotton is the most important warm-climate crop in the United States. The northern limit of cotton growing is approximately a mean summer temperature of 77° F. and a frostless season of 200 days. The annual precipitation requirements are in excess of 23 inches. Within these boundaries the Cotton Belt is found, the best cotton being produced when the weather is warm and moderately moist from April to August and when it is dry and cool during the autumnal picking period. On the other hand, cotton can successfully withstand periods of drought and still recover and produce satisfactory yields, if the season later becomes favorable.

Rice is an interesting crop by reason of its high water requirements, being grown to best advantage under conditions in which irrigation can be practiced. It is in fact a tropical plant, but can be grown in the warmer areas of the temperate zone. In Louisiana, the water requirement of rice has been found to amount to approximately one-half inch per day as an average for the 90-day growing season. The rainfall during this period amounting on the average to 20 inches, the remaining 25 inches must be supplied by irrigation. The temperature requirements are at least 75° F. as a mean for the crop season.

Two good examples of drought-resisting crops are found in olives and in the sorghums. The olive is sensitive to frost, but grows well in arid climates. Its very shallow root system enables it to absorb moisture after a light rain, and its leaves are of such a nature as to retard transpiration. Kaffir, milo, and other sorghums are grown in Texas, Oklahoma, and Kansas, in areas having an average annual rainfall of 15 to 30 inches. During periods of drought these crops cease growing, but they resume growth again whenever rain occurs.

Each of the various legume crops is largely confined to a rather definite climatic area although many of them can be grown over considerable climatic range if the soil is suitable. Alfalfa, originally grown mostly in the West and Southwest, has spread through the Dairy Belt, following the adoption of improved methods of soil management and the introduction of hardier strains. Cowpeas, velvet beans, lespedeza, crimson clover, and peanuts are the important legumes of the southern states. Red clover, soybeans, and sweet clover have about the same climatic requirements as corn. Alsike clover, Canada field peas, and canning peas grow best in cool, moist climates that are well suited to the oats crop.

Vegetables can be grown over a wide range of climatic conditions by reason of the large amount of care which farmers can afford to give to crops of such high acre values. In general, the market gardening centers of production correspond to the areas of dense population. Truck farming is carried on either in warmer climates where crops can be produced for early market or on soils which, by reason of their physical characteristics, are especially suited to the rapid growth of vegetables. The more succulent vegetables are being grown under glass and canvas, in ever-increasing acreages. Under the conditions thus produced, the climatic factors can be rather definitely controlled.

Of the fruits, the apple is by far the most important from the point of view of acreage. The climatic boundaries of this crop seem to be a mean summer temperature of 79° F., a mean winter temperature of not lower than 13° F., and an annual rainfall of not less than 18 inches. Cherries have about the same climatic requirements as apples. Peaches and plums will not endure as severe winter temperatures as will apples. Grapes, for wine and raisins, are grown largely in warm climates where the summer rainfall is fairly abundant and the autumn harvest period is dry. A considerable area of native grapes is found in the region of the Great Lakes where they are protected from extreme changes in temperature. The citrus fruits are grown only in regions where there are no severe frosts. In the United States, therefore, they are largely confined to southern California, the Rio Grande Valley, and the peninsula of Florida.

BIOTIC FACTORS AND CROP GROWTH

The wheat crop suffers in warm, humid climates from parasitic fungi which find a favorable environment under such conditions. The Hessian fly and the black stem rust are two important biotic agencies affecting this crop. Similarly, other crops are injured to varying extents by insects, fungi, bacteria, and other parasites whose development is favored by certain climatic conditions. While many of these biotic agencies are injurious, some of them are helpful in their effects and are beneficial to crop plants. Notable examples of these are found among those bacteria and fungi that live in the soil and have to do with making the organic, the mineral, and the atmospheric elements available for crop use. It seems desirable in this discussion to include these beneficial organisms, as well as all the parasitic organisms that harbor in the soil, among the edaphic factors, since the only opportunity for their control lies in some operation which alters the physical or chemical properties of the soil.

The effects of crops upon other crops grown in association with them, as well as upon the following crops, merit consideration. The explanation of the injury done to a crop by weeds is probably not so simple as might be anticipated from the ordinary statement of the fact of their competition with the crop for water, soil nutrients, and light. The variations in the yields of corn following clover and timothy are not due entirely to the known differences in the effects of these crops on the total content of nitrogen in the soil. That the yields of wheat following tobacco and potatoes are better than those after corn is well known, but as yet this has not been satisfactorily explained. There are many interesting problems in connection with plant associations and crop successions which are still to be solved.

Man is the most important biotic factor since, in addition to his ability to change in part the properties of the soil, to regulate the processes which take place in it, and to modify the effects of the climatic factors, he is also able to control to a certain extent the other biotic agencies which influence the growth of crops. It is a well-known fact that, by breeding and selection, it is possible to develop new varieties and strains of plants which may thrive over a wider range of climatic conditions, may have a greater resistance to disease, or may possess a greater capacity to secure from a given soil the elements required for larger yields.

EDAPHIC FACTORS AND CROP GROWTH

The edaphic factors vary in their effects upon crop growth, depending upon the influence of the climatic and biotic factors. Productivity is not a property that is inherent in the soil, but one that must be con-

TABLE 1

FLUCTUATIONS IN ACRE YIELDS DUE TO UNCONTROLLED FACTORS* (GARDNER)

Year	Corn, Bu.	Stover, Cwt.	Oats, Bu.	Straw, Cwt.	Wheat, Bu.	Straw, Cwt.	Hay, Cwt.
1882	44	40	42	23	27	31	..
1883	62	40	53	22	33	32	50
1884	79	29	48	15	33	24	36
1885	53	18	48	13	15	14	16
1886	48	27	64	28	11	16	41
1887	62	28	33	13	7	9	50
1888	78	58	41	15	23	13	32
1889	79	35	51	14	19	16	44
1890	57	30	23	10	27	36	31
1891	70	34	56	16	24	30	36
1892	56	34	39	16	22	25	31
1893	51	28	43	30	24	27	68
1894	46	32	26	14	21	30	67
1895	60	27	37	14	26	34	74
1896	43	18	62	21	23	14	22
1897	49	22	44	22	40	52	45
1898	70	37	30	18	33	38	58
1899	43	22	42	17	15	19	43
1900	35	22	40	19	8	7	20
1901	49	22	18	13	18	23	22
1902	42	25	44	9	27	18	69
1903	65	34	29	11	28	22	21
1904	45	24	33	24	9	11	61
1905	67	28	46	20	28	30	45
1906	73	28	24	11	29	26	42
1907	65	32	51	18	22	25	44
1908	51	23	40	21	28	28	59
1909	22	37	32	17	25	31	53
1910	58	30	53	19	23	30	43
1911	62	38	35	13	23	21	35
1912	67	28	51	16	25	28	39
1913	46	24	58	18	24	28	34
1914	57	28	41	11	22	21	27
1915	65	37	64	26	22	17	24
1916	53	24	48	22	24	25	51
1917	50	25	60	29	23	23	32
1918	55	15	52	15	23	20	32
1919	71	31	38	18	26	22	39
1920	66	36	59	21	25	22	49
1921	76	34	44	13	22	23	32
1922	62	24	49	19†	25	30	48
1923	49	33†	42	12	18	19†	19
1924	57	37	63	20†	21	25	40
1925	64	23†	50	13	32	24†	36

* Crop records of four plots on which corn, oats, wheat, and clover are being grown in rotation, the sequence being so arranged that all four crops appear each year.

† Yields probably influenced by supplemental treatments of lime.

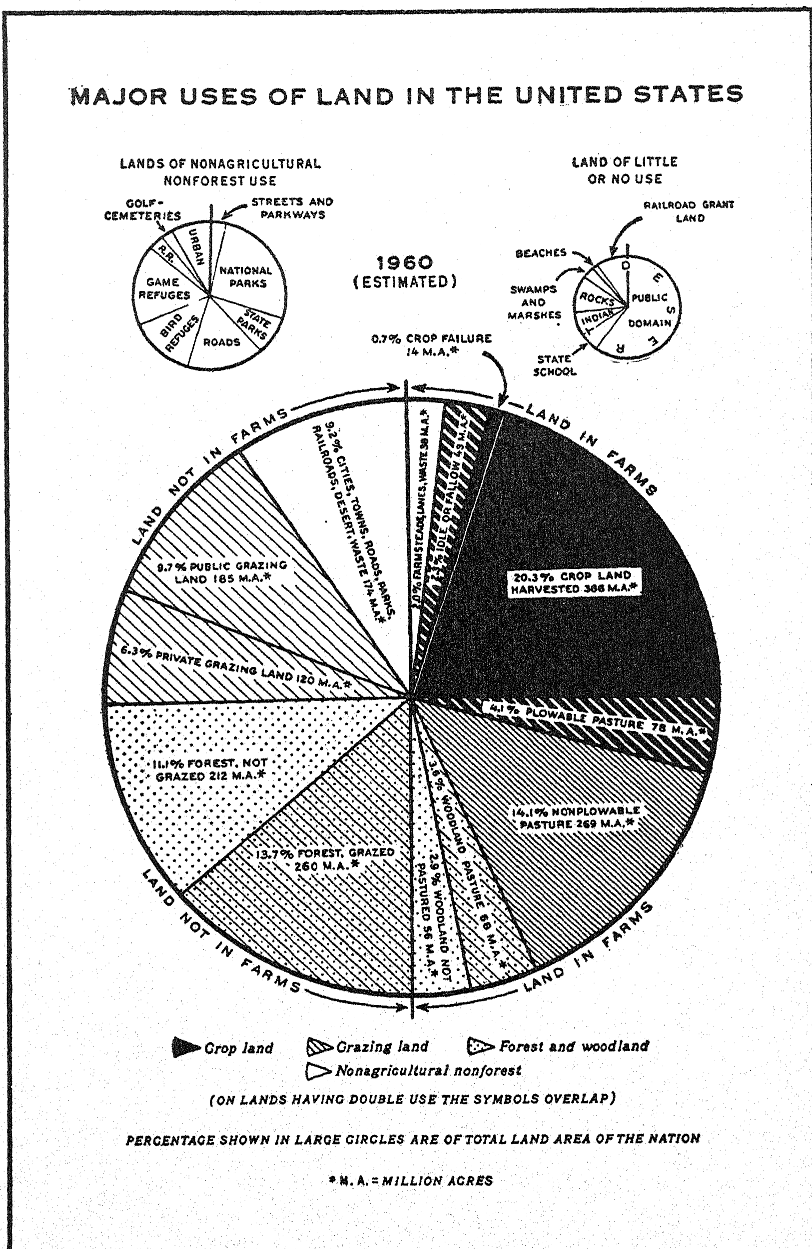

Fig. 3. Estimated use of land in the United States in 1960.

sidered in relation to the environment of the soil and the requirements of the crops to be grown.

The effects of the factors other than those of the soil, as they influence the growth of crops from year to year, will be apparent from a study of the fluctuations in yields produced by any given set of plots in a long-continued fertilizer test. The ones chosen as examples are located on the experimental farm at State College, Pennsylvania. Continuous records of the yields of these plots for a 44-year period are shown in Table 1. The rotation being followed on this series of plots is corn, oats, wheat, and clover. In order to have a continuous record for each crop there are four series of plots and, therefore, four plots having the same treatment. Each of these plots received the same amounts of the same complete fertilizer and should have produced practically the same yield as the others. The mechanical operations were identical on all the plots, except as changes in their frequency and type may have been necessitated by the weather. The climatic and biotic factors were not controlled, although their influence may have been somewhat modified by the soil treatments. The differences in yields to be noted from year to year are such as to make it apparent that the productivity of a soil must be considered in relation to the environment in which the soil happens to be. The environmental factors are dynamic. Their effects are never quite the same for any two crop seasons. Often they are very different.

Nevertheless, it is possible to effect very marked improvement in the productive capacity of any soil, even though it is subject to the

TABLE 2

Improvement in Acre Yields Due to Soil Treatments* (Gardner)

Soil Treatments	Corn, Bu.	Oats, Bu.	Wheat, Bu.	Hay, Cwt.
No fertilizer	33.7	30.5	12.4	21.9
Superphosphate	43.6	37.1	15.9	19.1
Phosphate and potash	52.1	42.3	19.1	39.9
Complete fertilizer	57.1	43.6	23.2	41.2
Manure (10 tons)	58.2	44.4	25.9	42.3
Manure (6 tons) and lime	62.5	43.7	23.8	42.2

* Average acre yields over a 44-year period of plots located at State College, Pennsylvania.

influences of the climatic and biotic factors. Thus, in the series of plots just mentioned, the average annual yield has varied greatly (see Table 2), depending upon the fertilizer and manurial treatments which the various plots have received, all other factors remaining constant except as their effects may have been modified indirectly by the materials that were added to the soil.

A 30-bushel increase in the yield of corn and corresponding improvements in the yields of other crops, for which the soil treatments alone are responsible, give some indication of the possibilities of improving the productive capacities of soils through the control of edaphic factors alone. It is essential to remember, in this connection, that the larger yields, produced as a result of the application of fertilizers, limestone, and manure, may have their explanation in part in the capacity of such treatments to modify the influence of the climatic and biotic factors. It must also be kept in mind that the climatic factors limit the distribution of a crop. Beyond a certain distance from the climatic crop center, the plant may not thrive no matter how carefully the soil is managed. But the farmer has the alternatives of modifying the soil to fit the needs of a given crop or of choosing another crop which may be better adapted to the soil under the environment in which it happens to be.

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CHAPTER II

NITROGEN AND MINERAL REQUIREMENTS OF CROPS

The analysis of a plant does not necessarily show its quantitative need for the elements that are found to be contained in it. So far as is known, there is nothing to prevent the entrance into the root hairs of any diffusible ion that may be present in the soil solution. Similarly, the gases of the atmosphere probably all have access to the interior of the plant in proportion to their solubilities in its sap. Nevertheless, it is to be expected that those elements which are common to all plants and which are present in them in considerable amounts have some necessary function to perform. It is possible that certain of these functions may be performed by more than one element. For example, there is evidence that potassium can be replaced in part by sodium, and that silicon may serve as a partial substitute for phosphorus. Plant

TABLE 3

Pounds of Elements in 10,000 Pounds Dry Weight of Corn (Latshaw)

Element	Symbol	Roots	Stalks	Leaves	Grain	Cobs	Entire Plant
Oxygen	O	316.3	1056.7	1234.8	1418.9	430.3	4457
Carbon	C	307.1	1071.5	1161.6	1400.7	429.1	4370
Hydrogen	H	41.4	141.6	164.7	218.9	59.4	626
Nitrogen	N	9.2	20.1	36.6	67.3	13.0	146
Silicon	Si	32.2	10.0	73.0	0.5	1.2	117
Potassium	K	3.5	30.5	39.7	13.4	4.5	92
Calcium	Ca	4.4	4.1	13.2	0.8	0.2	23
Phosphorus	P	0.8	2.1	5.8	10.6	0.8	20
Magnesium	Mg	1.2	3.8	5.9	6.2	1.0	18
Sulfur	S	1.8	3.8	6.7	4.3	0.2	17
Chlorine	Cl	0.8	5.0	6.3	1.0	1.1	14
Aluminum	Al	7.1	0.3	2.0	0.7	0.5	11
Iron	Fe	3.7	1.2	2.0	1.3	0.2	8
Manganese	Mn	0.5	0.4	0.9	1.2	0.3	3
Sodium	Na	other elements and errors*					78*
Per cent of total crop		7.2	24.1	28.1	31.3	9.3	100

* In a quantitative analysis of any material, the sum of the constituents seldom equals the weight of the original material. The quantity 78 includes sodium and other elements that were not determined.

analyses may be said to provide a clue to plant requirements and to permit fairly exact estimates of the amounts of nitrogen and mineral nutrients that are removed from the field in crops.

THE COMPOSITION OF THE CORN PLANT

A large amount of analytical data is available on the chemical composition of plants. Much of this is of doubtful value from the

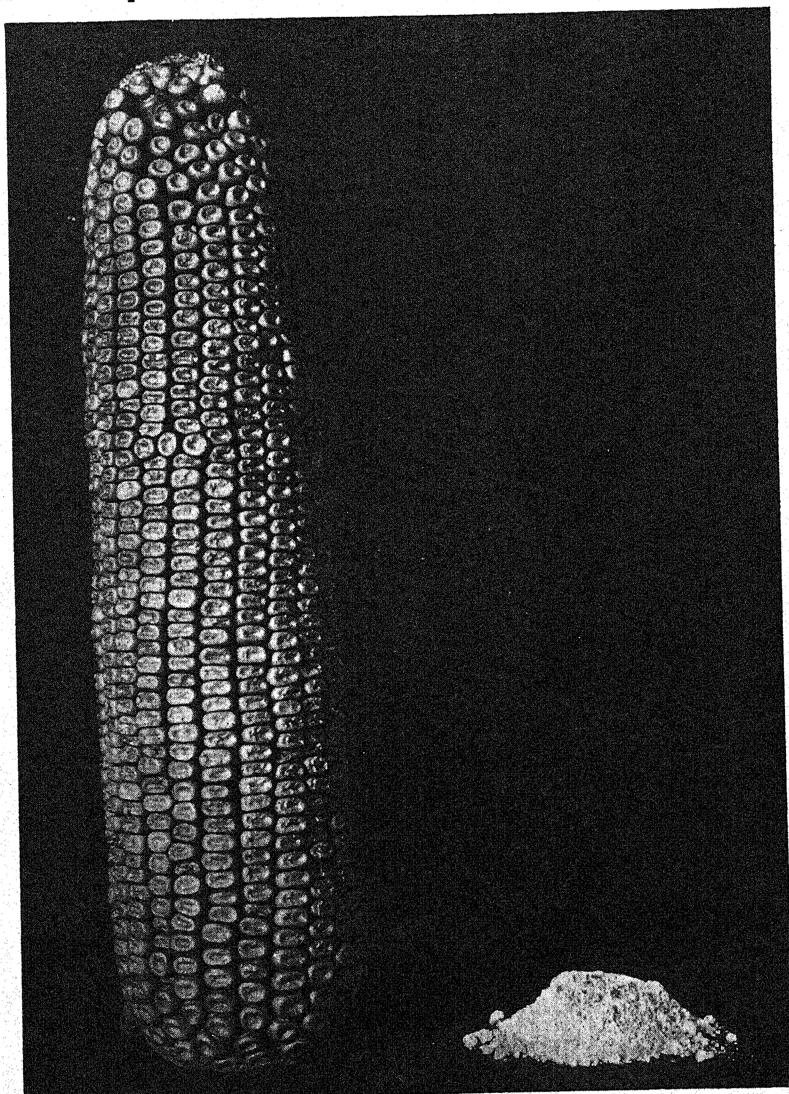

FIG. 4. An ear of corn and the ash from burning one like it.

quantitative point of view, at least for certain elements, because the earlier chemists, of necessity, made use of methods of analysis that are now known to be faulty. For that reason the more recent analyses are much to be preferred. Table 3 gives the elemental composition of a corn crop harvested at the stage at which it would ordinarily be cut for the silo. The yield on which the calculation is based is about 16 tons of silage corn, for such an amount as would have contained 10,000 pounds of oven-dried material. The accuracy of this estimate is subject to the limitations that the data are calculated from the analyses of only five stalks of corn, representing a single variety, grown on one soil type, and under the climatic environment of Manhattan, Kansas, as it happened to be during the summer of 1920.

Over 70 per cent of the corn crop at the siloing stage is found to be water. Nearly 95 per cent of the dry weight of the crop, remaining after the water has been driven off by heat, is made up of carbon, oxygen, and hydrogen. The total amount of mineral elements contained in the above estimated acre yield of corn was approximately 400 pounds, more than one-fourth of which was silicon.

THE SOIL IN RELATION TO THE COMPOSITION OF PLANTS

Within certain limits, the total content of any one of the soil nutrients in the plant is proportional to the quantity of that nutrient that was available to the plant in soluble form. It has been shown that plants will absorb much larger amounts of nitrogen and mineral nutrients from solution than seem to be required for optimum growth. Any excess of nitrogen and potassium is largely concentrated in the tops of plants, while that of magnesium, calcium, and phosphorus tends to accumulate in the roots. To a certain extent, it is possible to determine the amounts of the available nutrients in a soil from the analysis of a plant which has grown on it. The turnip is a notable example of a plant that has been used for this purpose by reason of its marked capacity to take up large amounts of phosphorus, if it is available in the soil. Comparative tests, made by growing the same species of plant on a number of soils and noting the instances in which deficiencies are indicated by the analyses of these plants, are of value in reaching decisions as to the quantity and the composition of fertilizer to apply.

It has long been known that the quality of pasture grasses bears some relation to the soil on which they are grown. The English farmer chooses certain pastures for young stock and selects others for fattening cattle. That there may be marked differences in the composition of different specimens of a given species of grass when grown to the same stage of maturity on different soils is indicated by the data in Table 4.

TABLE 4

VARIATION IN THE PERCENTAGE COMPOSITION OF KENTUCKY BLUEGRASS* (FORBES)

Locality	N	Ca	K	P	Ash
Lexington, Kentucky	1.91	.295	2.15	.373	7.08
Wooster, Ohio	1.77	.229	2.09	.272	6.22

* Averages of four samples in each case.

The soil in the Lexington area is exceptionally well supplied with calcium and phosphorus, whereas that at Wooster is notably deficient in these elements. There is evidence that the nitrogen and mineral content of pasture grasses can be materially increased by the use of liming materials and fertilizers.

VARIATION IN THE NITROGEN AND MINERAL CONTENT OF PLANTS

As would be expected, plants differ in their composition, depending upon the species and variety to which they belong, their stage of maturity at the time of harvesting, and the environment under which they have been grown. The following table is of interest in that it gives the nitrogen and mineral content of some of the more important

TABLE 5

POUNDS OF ELEMENTS* IN 1000 POUNDS OF PLANT MATERIALS (FORBES)

Materials	N	K	Ca	Mg	S	P	Ash
Corn	13.9	3.40	0.12	1.08	1.47	2.60	12.1
Oats	17.4	4.19	1.02	1.18	1.95	3.95	33.8
Wheat	16.5	5.20	0.50	1.30	1.98	3.73	16.4
Soybeans	63.1	19.13	2.10	2.23	4.06	5.92	50.6
Corn stover	8.8	17.18	4.72	0.86	1.74	0.95	65.2
Wheat straw	2.8	7.96	2.05	0.60	1.50	0.36	34.5
Clover hay	20.8	17.01	11.42	2.70	1.76	1.69	67.6
Bluegrass hay	14.6	12.90	3.08	2.20	3.07	2.22	48.2
Apples	0.4	1.18	0.04	0.05	0.06	0.09	2.7
Potatoes	3.3	2.72	0.05	0.58	0.25	0.47	6.7
Onions	2.6	1.83	0.33	0.17	0.76	0.41	5.5
Cabbage	1.9	1.73	0.41	0.15	0.63	0.18	5.0
Wheat bran	25.2	13.20	1.25	5.31	2.67	11.10	60.6
Cottonseed meal	57.4	16.56	2.66	5.48	4.90	13.52	69.8

* K × 1.2 = K_2O; Ca × 1.4 = CaO; Mg × 1.7 = MgO; S × 2.5 = SO_3; P × 2.3 = P_2O_5.

crop plants as shown by recent analyses. While studying these data, it is well to keep in mind the possible variations to be expected by reason of the influence of the factors enumerated above.

It will be noted that legume seeds, in comparison with the cereals, are high in nitrogen and ash. Likewise, legume hays contain higher percentages of nitrogen, calcium, magnesium, and phosphorus than do the non-legume hays, the cereal straws, and the corn stover. It is evident that the growing of clover and its removal from the field tend to exhaust the mineral nutrients of the soil more rapidly than would be true with most of the non-legume crops. Cereal straws are high in their content of silicon. Corn stover contains relatively large amounts of potassium. Considered from the point of view of an acre of produce, the members of the cabbage family are high in sulfur. Bluegrass has a nitrogen content approaching that of clover. The content of nitrogen in soybeans is found to range between 5 and 7 per cent, depending on the variety. Corresponding differences have been noted in the composition of the seed and other portions of the several varieties of a number of other crop plants.

CHANGES IN THE COMPOSITION OF PLANTS DURING GROWTH

Ordinarily, the percentages of nitrogen and mineral elements in plants are greatest during the earlier stages of growth, while starch and cellulose accumulate as the crops mature. With the production of seed there is a movement of nitrogen, phosphorus, magnesium, and sulfur to that part of the plant, there being a tendency for these elements to concentrate in the seed coats. Most of the calcium and potassium remains in the leaves and stalks. As the crop approaches maturity, some of its nitrogen and a large part of its mineral elements can be leached from it with water. A considerable portion of this water-soluble material is likely to be washed out by rains and, therefore, may not be removed from the field with the crop. This is demonstrated in

TABLE 6

PERCENTAGES OF ELEMENTS OF MATURE PLANTS SOLUBLE IN WATER (LE CLERC)

Plant	N	P	K	Na	Ca	Mg
Barley plant	2	36	65	52	..	45
Wheat plant	7	33	54	41	34	46
Oats plant	2	33	36	23	40	45
Apple leaves	8	32	36	20	9	12
Potato vines	3	25	18	22	6	12

the preceding table, which shows the percentage solubilities of the elements when the several plants were soaked in water under laboratory conditions.

There is evidence to the effect that much larger percentages can be dissolved if the leaching process is continued, as might occur where the crop remains in the field for some weeks after it has matured. The extent of the loss of nitrogen and mineral nutrients through crop removal is, therefore, quite variable, depending not only on the nature of the crop and the soil on which it was grown but also on the stage of maturity at which it was harvested, the length of time that the crop remained in the field after being harvested, and the climatic conditions that obtained.

ESSENTIAL AND NON-ESSENTIAL ELEMENTS FOUND IN PLANTS

Of the many mineral elements, potassium, calcium, magnesium, phosphorus, sulfur, iron, manganese, and boron are known to be essential to plants. Certain other mineral elements accelerate plant growth under some conditions. Among these are copper, molybdenum, zinc, arsenic, iodine, and lithium. Considerable uncertainty exists as to the need of sodium, silicon, and chlorine in plants, although all three have been found useful. A considerable number of other elements are commonly found in plant ash, as is shown in the following table. It is possible that further study of this problem will show that some of these elements are essential to certain species of plants and not to others.

TABLE 7

PERCENTAGES OF OXIDES OF RARER* ELEMENTS IN PLANTS (ROBINSON)

Element	Oxide	Alfalfa	Beet	Cabbage	Cotton	Tobacco	Blue-grass
Titanium	TiO_2	.001	†	.001	.001	.001	.002
Aluminum	Al_2O_3	.068	.018	.023	.075	.062	.050
Manganese	MnO	.007	.0067	.0064	.0123	.0123	.0037
Barium	BaO	.008	.0006	.003	.004	.018	.004
Strontium	SrO	.006	.006	.012	.005	.022	.002
Sodium	Na_2O	.36	.09	.24	.38	.39	.02
Lithium	Li_2O	‡	‡	‡	‡	‡	‡
Rubidium	Rb_2O	.0018	.0003	.0013	.0006	.0038	†
Chlorine	Cl	.18	.71	.85	.16	2.50	.44

* Some of these elements are not properly classified as rare; but they are presented because they are not usually mentioned in plant discussions although many of them are found in considerable amounts in soils.

† Not present. ‡ Usually present in traces.

There is great need to catalog the differences, rather than the similarities, in the mineral requirements of crop plants.

THE MINERAL THEORY

Justus von Liebig, a famous German chemist who was prominent in chemical circles about the middle of the nineteenth century and who was known as the father of agricultural chemistry, formulated the working hypothesis that "the crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in manure." Liebig pointed out that it had been proved that the carbon of plants comes from the carbon dioxide of the air. He believed that their nitrogen, likewise, was secured from the ammonia in the atmosphere. His statement was meant, therefore, to emphasize the importance of the mineral elements in soil and plant economy. Liebig argued that the exhaustion of soils was simply the result of the continued removal of these mineral nutrients in the harvested crops. Accordingly, he suggested the use of mineral salts that carry these elements and experimented with these "patent manures" on his own farm, getting such good yields as to arouse the curiosity of all who passed by. As a result, there was begun what has since developed into an enormous fertilizer industry whose function is the supplying, in available forms, of the elements that plant analyses show are being removed from soils by crops.

It has been pointed out that crop growth is influenced by many factors, of which those of the soil comprise only one group. Even within this group, water, nitrogen, the temperature, the reaction of the soil solution, and other edaphic factors are equally as important as the mineral nutrients. Another phase of the problem which the mineral theory of Liebig fails to take into consideration is that any factor in excess may become a limiting factor. For example, many plants become chlorotic following the use of large amounts of lime on the soil on which they are growing. The excess lime interferes with the plants' absorption of such elements as manganese, iron, zinc, and potassium. Further, even if all the factors are at the optimum, the limit of growth of the plant is finally fixed by the capacity of the protoplasm to do work.

Taking these various matters into consideration, if all the factors except one were at the optimum, the yield of the crop would be expected to be somewhat proportional to the quantity of this limiting factor which was supplied, until the optimum effect from its use also was reached. However, all factors are interrelated in their action, and the effect of a deficiency of any one of them is determined by the nature of its relation to the others as well as by the need of the crops for that particular factor.

EFFECTS OF VARIOUS FERTILIZER SALTS ON CROP YIELDS

It has been shown that various chemical compounds when added to soils — at least to those that have been under cultivation for a considerable period of years — will very materially increase the rate of growth, the total yield, and the quality of the crops grown on them. The example given below is simply one of many such tests that have been made. It is distinctive only in the sense that the applications of the fertilizer salts were quite heavy, and the unfertilized soil (a Dekalb[1] silt loam) was very unproductive, although not more so than large acreages of land that are to be found in the eastern part of the United States. The data are calculated on the acre basis and give the total production of dry weight of crops for the entire fifteen-year period during which the experiment was in progress.

TABLE 8

EFFECT OF VARIOUS CHEMICAL COMPOUNDS ON CROP YIELDS* (BEAR)

Compounds	Amounts Added, Lb. per Acre	Produce in Lb. per Acre	
		Actual	Relative
None	0	40,034	100
Nitrate of soda	4,200	41,195	103
Muriate of potash	1,625	41,565	104
Nitrate and muriate	5,825	52,215	130
Superphosphate	4,200	63,415	159
Phosphate and muriate	5,825	76,995	192
Nitrate and phosphate	8,400	95,940	240
Nitrate, phosphate, muriate	10,025	117,910	295
Same and burned lime	14,525	120,605	301

* Total dry weight of crops produced on an acre during a fifteen-year period.

The data show that each of the compounds employed, when used alone or in combination with one or more of the others, increased the crop yields. If the conception of one limiting factor operating at a time were strictly applicable, one would not expect nitrate of soda and muriate of potash to increase the crop yields when an even larger increase was produced by the use of superphosphate alone. It is now known that all these salts have indirect as well as direct effects on the

[1] This soil is not naturally very fertile, but its productive capacity is readily increased by the use of lime and fertilizers, as the data in Table 8 plainly indicate.

crop, through their action on the soil. But it seems apparent that the interrelationship existing among the various compounds in their effects on plant growth is too complex to be explained by such a simple statement as Liebig's mineral theory.

THE SOIL-PLANT-ATMOSPHERE-SOIL CYCLE

Modern field-irrigation systems have amply demonstrated that the yield and quality of crops can be improved in humid regions by the use of more water than the rain supplies. Greenhouse studies have shown that plants are able to use carbon dioxide at a more rapid rate than it can be secured from the ordinary atmosphere. Yet dependence is usually placed on the natural water and carbon dioxide cycles, which may be completed in a relatively short time and which suffice to meet the ordinary requirements of plants. Similarly, there are cycles for the return to the soil of the elements nitrogen and sulfur.

Most of the mineral elements do not complete the cycle naturally and for that reason must be supplied in commercial forms. For these elements, the problem is one of determining the rate at which they are removed by crops, the losses that may occur by other means, and the extent to which any compensatory processes may operate to renew the supply in the soil, in order to determine what supplemental treatments may be essential. Where land has been under cultivation for some years, it is not uncommon — in fact, it is the rule — that the addition to the soil of soluble compounds of nitrogen, phosphorus, and potassium, and the use of the basic compounds of calcium and magnesium, will increase the crop yields. With increasing frequency, carriers of boron, manganese, zinc, and copper are being supplied to good effect.

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CHAPTER III

THE WATER REQUIREMENTS OF PLANTS

The moisture relationships of plants are of primary importance in determining their natural distribution. These relationships may be considered from two standpoints, namely: that of the water requirements of plants and that of the supply of water which is available for their use. Water requirement may be defined as the ratio between the quantity of water transpired by plants and the amount of dry matter produced by them. It varies chiefly with the nature of the plant, the evaporating power of the air, and the intensity of the sunlight. The water supply is normally determined by the rainfall and the extent to which this water escapes beyond the reach of plants through drainage, evaporation, and transpiration. This chapter is concerned with the water requirements of crop plants, the factors which modify these requirements, and the extent to which they are met naturally in the regions in which the various crops are being grown.

NATURAL VEGETATION REGIONS OF THE UNITED STATES

The accompanying map of the United States shows the distribution of the native vegetation. It is of considerable interest and significance by reason of the fact that this vegetation is an expression of the effects of the climatic factors that operate in the various regions. It is to be expected that, when the many subdivisions of these regions have been established by ecologists, their centers will be found to correspond to those of the areas that are best adapted to the growth of the various crop plants. Of particular interest is the very evident importance of the moisture factor in determining the natural distribution of forests and grass lands. It is no less important in determining the centers of production of the extensively cultivated field crops. Furthermore, within any region whose climate is suitable for a given crop, it is this same moisture factor which, more than any other, is responsible for the fluctuations in the yields produced.

CORRELATION BETWEEN RAINFALL AND CROP YIELDS

Samuel Johnson, writing in 1870, said: "It is a well-recognized fact that, next to temperature, the water supply is the most influential fac-

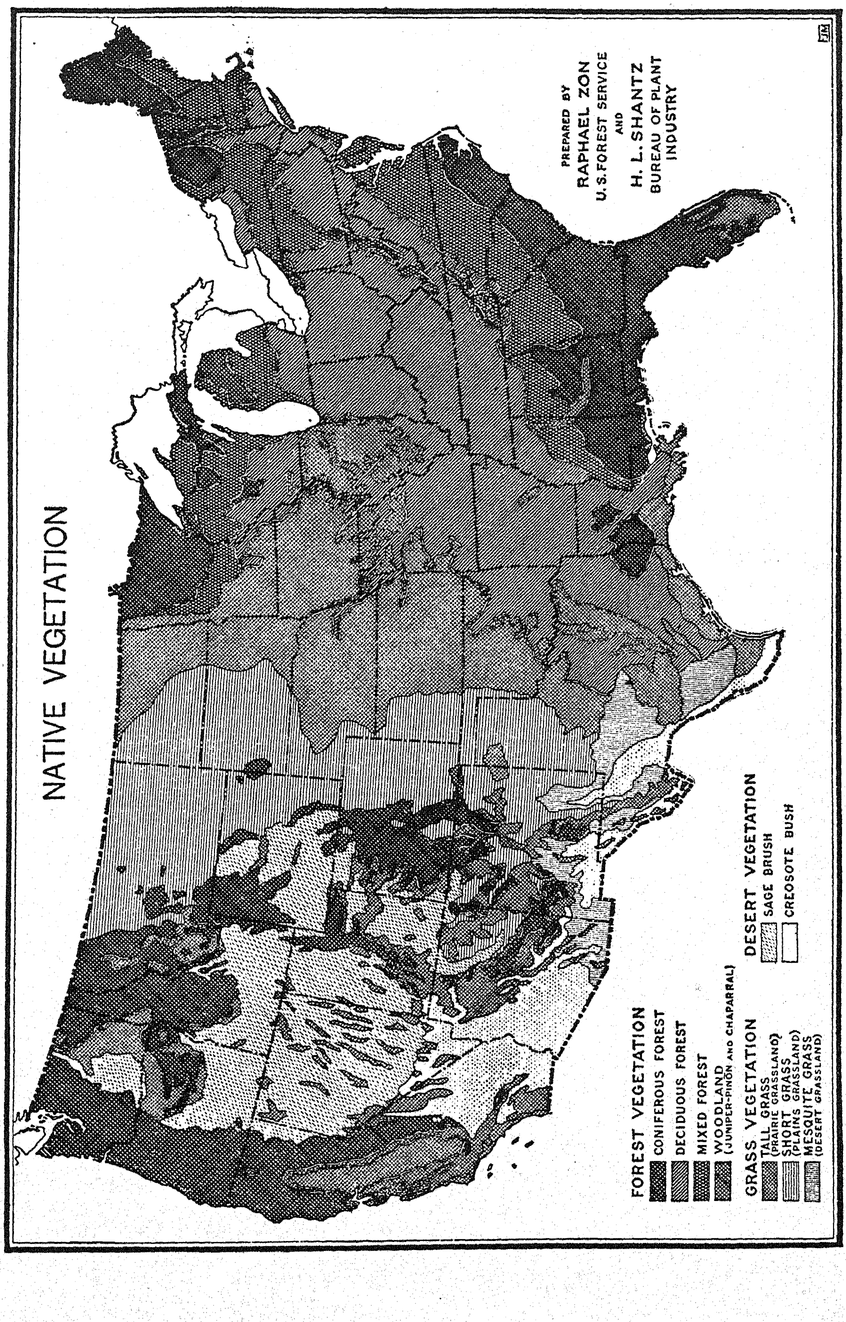
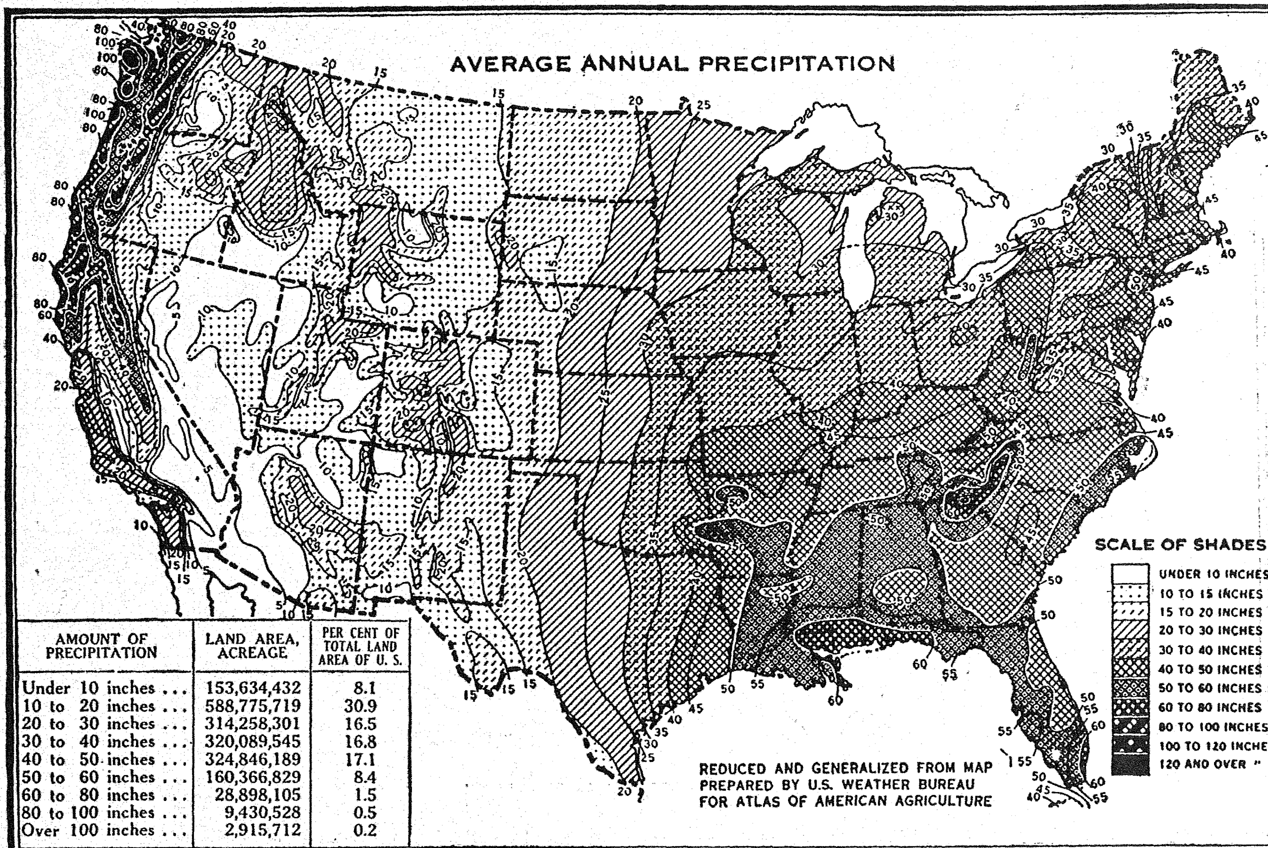


FIG. 5. Climate is the controlling factor in plant distribution.



AMOUNT OF PRECIPITATION	LAND AREA, ACREAGE	PER CENT OF TOTAL LAND AREA OF U. S.
Under 10 inches . . .	153,634,432	8.1
10 to 20 inches . . .	588,775,719	30.9
20 to 30 inches . . .	314,258,301	16.5
30 to 40 inches . . .	320,089,545	16.8
40 to 50 inches . . .	324,846,189	17.1
50 to 60 inches . . .	160,366,829	8.4
60 to 80 inches . . .	28,898,105	1.5
80 to 100 inches . . .	9,430,528	0.5
Over 100 inches . . .	2,915,712	0.2

FIG. 6. In a latitude and elevation favorable for the production of crops, precipitation has first place and temperature second.

tor in the production of the crop." After studying the relationship between rainfall and crop yields, J. Warren Smith later showed that in a latitude and elevation favorable for the production of crops, precipitation has first place and temperature second. Smith reported that there was a high degree of correlation of rainfall, for the month of July, and of corn yields, in the eight most important corn-producing states, for a twenty-five-year period. He pointed out that, when the rainfall in July averaged less than 3.4 inches, the yield of corn in those eight states averaged 10 bushels less per acre than when the rainfall was more than 4.4 inches.

Crops that are being grown at considerable distances from their climatic centers, in the direction of decreasing rainfall, yield to those that suffer less from drought. It is for this reason that the sorghums are substituted for corn, toward the southwest. These crops have water requirements which are quite similar to those of corn, but they have the remarkable capacity to withstand dry weather without apparent injury. During periods of drought, such crops remain dormant. When rain comes, the normal rate of growth again takes place. This is one of the important reasons why cotton replaces corn in the South, since cotton is able to withstand drought and still produce a fair crop, even if the rain is late in coming. The corn plant has only one ear, whereas the cotton plant has many bolls whose critical periods as to moisture supply do not all come at the same time. Alfalfa, with its long tap root, survives drought better than the shallow-rooted clovers.

EFFECTS OF INCREASING AMOUNTS OF IRRIGATION WATER

A somewhat better idea of the relationship between water supply and crop yields may be secured by a consideration of irrigation investigations in the western states. The point of greatest economic importance is that of determining when to discontinue increasing the application of water to any one acre and to begin enlarging the acreage under irrigation. In Table 9 are shown some crop-yield data on sugar beets and potatoes in irrigation tests in Utah. The water was supplied at rates of 1, 2, 3, 4, and 5 inches per week, by the flooding method. The total yearly rainfall amounted to 17.26 inches as an average for the five-year period, of which 1.20 inches fell during the three summer months. The soil, which was a well-drained clay loam, was manured each year so that there was probably no lack of nitrogen and mineral nutrients to limit the growth of the crops.

The optimum application of water for sugar beets was 20 acre-inches, applied at the rate of 2 inches a week. For potatoes, 50 inches did not seem to be excessive. Experiments with other crops showed similar curves of increase from applications of irrigation water, the optimum quantity depending upon the crop and the season.

TABLE 9

Acre Yields* of Crops with Varying Amounts of Irrigation Water (Harris)

Water Applied, Acre-inches	Sugar Beets			Potatoes	
	Roots, tons	Tops, cwt.	Sugar, per cent	Tubers, bu.	Tops, cwt.
0	10.3	102	15.2	96	44
10	18.2	215	16.0	248	84
20	19.8	235	16.5	254	90
30	19.7	217	15.6	249	90
40	19.3	237	15.4	279	100
50	19.2	243	15.8	286	102

* Five-year-average acre yields.

THE RAINFALL-EVAPORATION RATIO

The climatic centers of production of the various crops, in so far as water relationships are concerned, are determined not so much by the

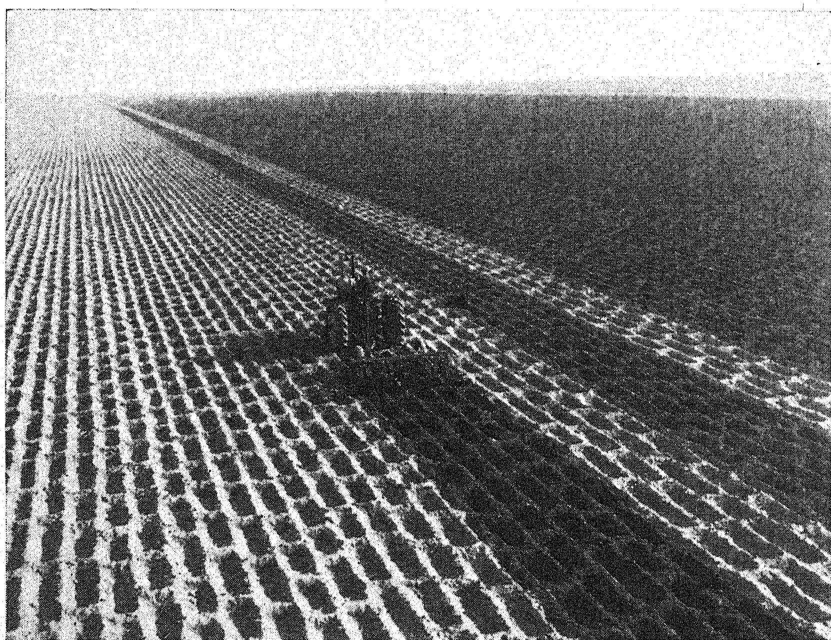


Fig. 7. Basin-listing to catch every drop of rain, in an area where the rainfall is less than 30 inches annually, and the rainfall-evaporation ration is less than one-half.

amount of rainfall, beyond a certain point, as they are by the rate of loss of water by evaporation. The ratio between the rainfall and the rate at which water will evaporate from a free water surface, called the *rainfall-evaporation ratio,* is probably the best expression of the moisture factor which has yet been suggested. It has been shown that this ratio is more than 1, in the typical forest centers of the Atlantic seaboard, the Gulf coast, and the Great Lakes region, and between 0.6 and 0.8, in the natural prairie regions of Illinois and Iowa. The desert may be said to begin when the ratio falls to less than 0.2.

Lines connecting points of equal rainfall tend to run north and south, in the United States, whereas those connecting points having the same rainfall-evaporation ratio bend far to the east. In the absence of opportunity to supply water by irrigation, the distribution of crops as between semi-arid and humid climates will be determined quite largely by the water requirements of these crops and the rainfall-evaporation ratio.

THE FUNCTIONS OF WATER IN PLANTS

Water has three important functions to perform in the plant. It is required in considerable amounts for food purposes; it is the solvent in which nitrogen and mineral nutrients enter the plant; and its transpiration is an effective means of regulating the temperature of the plant. Its importance as a food is evident from the fact that hydrogen and oxygen, which have their origin largely in water, constitute a high percentage of the mature plant. If it were not for the fact that water provides a continuous medium for diffusion purposes, the mineral nutrients would have no means of access to the plant tissues. The significance of the transpiration factor, as a temperature control, is apparent when one knows that between 200 and 500 pounds of water are given off by the leaves of plants for every pound of dry matter produced. If the quantity available falls far below this need, the plant goes through the successive stages of wilting, firing, and dying.

WATER CONTENT OF PLANTS

If the corn crop is used as an example, it is found that, at the stage of maturity at which this crop is ordinarily cut for the silo, its water content is nearly 75 per cent of its weight. Only a little over one-quarter the given weight of ensilage remains after it has been thoroughly dried at 105° C. This dry material contains a considerable additional amount of hydrogen and oxygen, most of which had its origin in water taken up from the soil by the roots. As a result of photosynthetic processes in the leaves, simple organic compounds are produced in plants by the combination of water and carbon. These, together with nitrogen and the mineral elements, are later synthesized into the more or less complex organic compounds which comprise the dry matter of plants.

Vegetables, root crops, and fruits are made up in large part of water. While they are important in the diet as sources of carbohydrates, mineral elements, and vitamins, still they do not supply such amounts of food and minerals as their acre-weights would indicate. In fact, for a crop like tomatoes, in which the vines are returned to the soil and the fruit contains as much as 95 per cent of water, the farmer, in effect, is selling water at a very high price. The fruit of tomatoes, like the sugar from beets and the butter from milk, is made up mostly of water and air, and little is lost from the soil by their sale.

TABLE 10

PERCENTAGE WATER CONTENT OF PLANT PRODUCTS (FORBES)

Fruits and Vegetables		Mature Grains		Fresh Green Forage	
Apple	85	Buckwheat	12	Alfalfa	75
Beet	87	Corn	14	Bluegrass	68
Cabbage	93	Cottonseed	9	Corn silage	74
Carrot	88	Oats	9	Rape	83
Onion	87	Rice	10	Red clover	74
Potato	82	Soybeans	9	Sweet clover	76
Pumpkin	92	Wheat	12	(Clover hay)	8

WATER AS A MEDIUM FOR THE TRANSFER OF NUTRIENTS

If an animal or vegetable membrane, such as a cell wall, is interposed between two salt solutions of different concentrations, the substances in solution, as well as the water, tend to pass through the membrane until the concentration of each dissolved salt is the same on one side of the membrane as on the other. Similarly, nitrates and mineral nutrients in the soil solution tend to penetrate the outer walls of the root hairs and find their way from cell to cell into the water-conducting tubes of the xylem, through which they are transferred to the farthest portions of the plant. The xylem contains no interfering cross walls to slow down the movement of the water and its dissolved salts, but access to the cells of the tissues along the way is only possible as the solutes and solvent pass through the outside walls of these conducting tubes.

As ions of the dissolved salts are used in the construction of tissues, in the formation of insoluble compounds, or in the synthesis of undissociated molecules, more of these ions move into the root hairs from the soil solution until the concentration of each ion is again as high inside the plant as it is in the soil solution. In the laboratory, the movement of ions takes place with equal rapidity in either direction through an interposed plant membrane, depending entirely on the relative concentrations of each of the several ions on either side of the membrane. In the plant, the protoplasmic colloids retard the return flow of a nutrient ion once it has penetrated the cell wall. Peculiarly, also, the salt concentration on the inside of the plant tends to become greater than it is in the soil solution. A large percentage of these entrapped ions do not seem to be tied up in structural combinations within the plant, yet they appear to function in its growth.

It is apparent that water serves as a carrying agent for nitrogen and mineral nutrients under conditions in which the water is passing through tubes without any interposed membranes. This is true when water is moving upward in the soil by capillarity or when it is in movement in the xylem of the plant. The interposing of a membrane, such as a cell wall, alters the situation and makes the water merely a medium through which the ions move in response to attractive forces operating within both the plant and the soil.

WATER AS AN AGENT FOR REGULATING THE TEMPERATURE

The movement of the water itself through the root hairs and into the xylem is caused in large part by the concentration of dissolved materials, which is much higher in the cell sap than in the soil solution. The direction of flow of the water is determined by the total concentration of particles, including both undissociated molecules and ions. The cell sap contains the entrapped ions secured from the soil solution and the soluble compounds that have been synthesized by the plant from carbon dioxide and water. As water escapes from the leaves by transpiration, the concentration of the soluble materials in the cells becomes greater and the rate of flow of water into the plant is increased. Something more than this pressure is probably required to lift the water to the tops of tall trees. The manner in which this is done has not been satisfactorily explained.

The tendency of the molecules and ions inside the cells is to move in the direction of the lower concentrations that occur in the soil solution. The plant colloids prevent their escape from the cells, and equilibrium can be re-established only by movement of water into the plant. As a result, what is known as osmotic pressure develops within the cell. This pressure cannot be readily measured directly, but it can be measured by determining the height to which the incoming water that is moving toward this higher concentration will pile up on that side of the membrane. Experiments have shown that the molecular weight, in grams, of an undissociated compound dissolved in 22.4 liters of water exerts, at 0° C., an osmotic pressure of 1 atmosphere, or the equivalent of the weight of 760 millimeters of mercury. For compounds that dissociate in water, the quantity required is proportionally less, depending upon the degree of ionization. The osmotic pressure of the cell sap is usually 5 to 10 atmospheres, or 75 to more than 100 pounds a square inch.

If, for any reason, the soil cannot supply the water as rapidly as it is lost from the plant by transpiration, wilting occurs. If this is only temporary, no harm will ordinarily result. If it continues for some time, firing of the lower leaves usually takes place, and gradually the entire plant dies. When plants are transplanted, the absorbing root hairs are broken off and wilting likewise occurs. In transplanting tobacco and other plants, it is common practice to supply extra water as the plants are being set. Fertilizer salts are added to this water as a means of giving the plants a quick start. A good starter-solution can be made by dissolving 1 pound each of potassium chloride and ammonium phosphate and ½ pound each of nitrate of soda and urea in 50 gallons of water. Care must be taken not to use more than these amounts of fertilizer.

When large amounts of soluble salts are applied to the roots of plants, the movement of the water is from the plant to the soil. Plasmolysis of the cell contents takes place, and death may result. Difficulty is sometimes encountered in this connection as a result of heavy applications of soluble fertilizer salts in the row or hill. Similarly, plants are often killed by alkali in those areas in which the rainfall is limited. As more and more of the soil water is lost by transpiration, a point is finally reached at which the effective concentrations in the soil solution and the plant sap are identical, and no further movement of water into the plant takes place. Further loss of water from the soil by evaporation causes an additional concentration of the soil solution, and the crop then loses water and is injured or killed.

It sometimes happens that the humidity of the atmosphere, following rains, is such that transpiration from the leaves of plants is very much reduced. Under such conditions, if the sunshine is bright, the phenomenon known as scalding occurs. This indicates the extent to which the temperature is kept under control by transpiration and the injury that may result if this function is not performed.

WATER REQUIREMENTS OF A FEW TYPICAL CROP PLANTS

The water content of a plant is not an index of the water requirements of that plant. Transpiration studies have shown that 250 to 300 or more pounds of water pass through the corn plant and are lost into the air, for every pound of dry matter produced. This water is required as a means of regulating the temperature, as well as for supplying the plant with nitrogen and mineral nutrients. Calculated on the acre basis, it is found that a 100-bushel crop of corn will require about 11 acre-inches of water. This is very nearly the average rainfall of the Corn Belt for the three months of June, July, and August, the important months in the growth of this crop. Since a considerable percentage of the water that falls as rain is lost by drainage and evaporation, it is apparent that, unless a supply of water from previous rains has been stored in the soil for the use of the corn crop, the crop will suffer from the lack of this very important constituent.

A mature apple tree probably transpires as much as a barrel of water a day during the growing season. Calculated on the acre basis of forty trees, this would indicate a daily need of 5 tons of water. Similarly, the vegetable crops require large amounts of water and usually suffer because of a deficiency unless some system of irrigation is practiced. The hay crops thrive under conditions of abundant moisture supply and, for that reason, are grown to best advantage in the northeastern part of the United States or, as with alfalfa, under irrigation.

RELATIVE WATER REQUIREMENTS OF CROPS

So many factors influence the rate of transpiration of water by plants that it is not possible to give an absolute value to their water requirements. It is not even safe to assume that the relative water requirements of plants, as calculated in any climatic region, will apply when these plants are grown under different conditions of climate and soil. These limitations must be kept in mind in studying the following table

TABLE 11

Relative Water Requirements of Crops* (Briggs and Shantz)

Crop	Per Cent	Crop	Per Cent	Crop	Per Cent
Millet	85	Sugar beet	110	Cowpea	155
Sorghum	90	Cabbage	145	Soybean	180
Corn	100	Watermelon	160	Hairy vetch	185
Wheat	140	Potato	170	Sweet clover	210
Oats	160	Turnip	175	Red clover	215
Cotton	175	Cucumber	195	Canada pea	215
Rye	185	Rape	200	Crimson clover	220
Rice	190	Pumpkin	225	Alfalfa	225

* On basis of water requirement of corn = 100.

which gives the relative water requirements of crops at Akron, Colorado, using corn at 100 as the standard. The actual water requirement of corn at this location, as an average of a three-year period, was 368 pounds for each pound of dry matter produced.

SOIL AND CROP MANAGEMENT IN RELATION TO WATER REQUIREMENTS

There are three things which a farmer might do that would affect the water requirements of his crops. The most important of these is to choose crops whose requirements are low or high, depending upon the water supply. The quantity of water can be readily regulated, within certain limits. When, however, the cost of controlling it reaches a certain point, there may be a chance to choose between making further expenditures to regulate the supply and growing another crop which is adapted to soil and climatic conditions as they are. This is often the deciding factor in determining whether the land shall be kept in pasture or be put under cultivation. The classification of plants into xerophytes, mesophytes, and hydrophytes recognizes differences in their water relations. Most of the common crop plants belong to the mesophytes, but some important ones are grown under xerophytic or hydrophytic environments.

It has also been shown that the number of stomatal openings on the leaves of plants is very much less if the soil does not contain an excess of water during the early stages of the growth of a plant. It is a matter of common observation that a corn crop which has its beginning in a dry period can withstand drought during the latter part of the season much better than one that has been subjected to wet weather during its early history. An explanation is found in the smaller number of stomata on the leaves and in the smaller loss of water from them.

TABLE 12

Relation between Water Supply and Number of Stomata (Duggar)

Water in Soil, Per Cent	Corn Plants		Wheat Plants	
	Weight*	Stomata	Weight*	Stomata
38	3.63	181	3.9	103
30	3.54	130	6.4	85
20	3.36	129	4.7	82
15	2.35	124	3.7	81
11	1.56	107	3.7	59

* Weight in grams.

Another fact which has been established is that the amount of water transpired for each pound of dry matter produced is much less on good soils than on poor ones. This is indicated in the following table, in which comparisons were made between the water requirements of corn when grown on manured and unmanured soils of various degrees of natural productivity, during a good crop season, in Nebraska.

TABLE 13

THE SOIL IN RELATION TO WATER REQUIREMENTS OF CORN (KISSELBACH)

Class of Soils	Yield*	Requirement†	Yield*	Requirement†
Unmanured Soils:				
Poor soil	100	550	142	376
Intermediate	163	479	330	290
Good soil	239	392	417	262
Manured Soils:				
Poor soil	333	350	364	295
Intermediate	366	341	437	274
Good soil	419	346	447	250

* Relative yields on basis of crop produced on unmanured poor soil = 100.

† Requirement expressed as pounds of water transpired to produce one pound of dry matter.

The data indicate that one pound of water will serve to produce twice as much crop on a good soil and in a favorable season as it will under unfavorable conditions of soil and weather.

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CHAPTER IV

THE ORIGIN AND CLASSIFICATION OF SOILS

Soil is a product resulting from the disintegration and decomposition of rocks and of plant and animal materials. If the processes in operation are largely physical, as may be the case in arid regions, the soil will resemble the parent rock quite closely in its chemical and mineralogical composition, the difference being chiefly a matter of fineness of division. If, in addition, the rock particles are subjected to the solvent and leaching action of water containing carbonic and other acids and various salts in solution, such as occurs in humid regions, the inorganic part of the soil may become largely an accumulation of finely divided, relatively insoluble, mineral residues which bear little resemblance to the original rocks.

TABLE 14

PERCENTAGE CHEMICAL COMPOSITION OF ROCKS (CLARKE)

Oxides	Igneous Rocks	Shales	Sandstones	Limestones
SiO_2	59.14	58.10	78.33	5.19
Al_2O_3	15.34	15.40	4.77	0.81
Fe_2O_3	3.08	4.02	1.07	0.54
FeO	3.80	2.45	0.30	....
MgO	3.49	2.44	1.16	7.89
CaO	5.08	3.11	5.50	42.57
Na_2O	3.84	1.30	0.45	0.05
K_2O	3.13	3.24	1.31	0.33
H_2O	1.15	5.00	1.63	0.77
TiO_2	1.05	0.65	0.25	0.06
CO_2	0.10	2.63	5.03	41.54
SO_3	0.13*	0.64	0.07	0.28*
P_2O_5	0.30	0.17	0.08	0.04
MnO	0.12	....	....	0.05
Others	0.28	0.05	0.05	....

* Includes elemental sulfur calculated as the oxide.

ROCKS — AND SOILS DERIVED FROM THEM

Rocks vary greatly in their chemical composition, as will be noted in Table 14. Igneous rocks, on the average, contain about 75 per cent silica and alumina. Limestones are made up mostly of calcium and magnesium carbonates. Yet the soils that are formed from these very different kinds of rocks are often surprisingly similar in chemical composition. In fact, if rainfall and temperature conditions are identical and the topography is relatively level, there is a tendency toward the production of a uniform soil product, no matter what the original rock may have been.

Even under such diverse conditions as have existed in the various parts of the humid regions of the United States, there is a striking similarity in composition of the soils that have been formed. This is well illustrated in Table 15, which gives the analyses of four widely separated soils which had their origin in four different kinds of rock. The Cecil series consists of lateritic soils that were formed under warm and humid climatic conditions. The Cherokee series is made up of prairie soils. Those of the Penn and Decatur series are gray-brown podsolic soils. Yet the content of silica, alumina, and iron oxide in the surface horizons of each of these soils totals between 90 and 95 per cent.

The younger soils are, the greater their resemblance to the parent rock material. Young soils are shallow and have poorly defined horizons, as contrasted with the distinct zones which distinguish those of greater maturity.

TABLE 15

PERCENTAGE COMPOSITION OF SOILS DERIVED FROM VARIOUS ROCKS* (BENNETT)

Oxides	From Granite	From Shale	From Sandstone	From Limestone
SiO_2	66.49	86.96	74.33	79.35
Al_2O_3	17.11	4.86	11.00	8.89
Fe_2O_3	7.43	2.86	4.64	4.44
TiO_2	1.02	0.69	1.04	1.15
MgO	0.31	0.43	0.69	0.39
CaO	0.36	0.71	1.13	0.63
Na_2O	0.16	1.07	1.53	0.24
K_2O	0.62	0.91	1.57	0.67
MnO	0.51	0.07	0.13	0.07
P_2O_5	0.20	0.07	0.16	0.18
Series	Cecil	Cherokee	Penn	Decatur
Texture	Clay	Silt loam	Silt loam	Clay loam
Sample depth (in.)	0–6	0–6	0–9	0–4

* The range in chemical composition of soils derived from any one class of rocks is often greater than that of soils derived from different classes of rocks.

To a certain extent, the tendency toward similarity in chemical composition of soils holds true with regard to their physical and biological composition as well. All agencies acting on rocks to produce soils tend to effect reductions in the size of their constituent particles. These particles pass through the successive stages of gravel, sand, silt, and clay. As they are moved from place to place through the action of wind and water, their microbiological population is carried with them. As a result, most of these microorganisms which function in soils are well distributed, except as conditions may have developed in some cases which were inimical to the growth and reproduction of certain species.

DIFFERENCES IN THE COMPOSITION OF SOILS

Notwithstanding the tendency in the direction of uniformity of the soils of humid regions, soil differences at any given time are many. Some of these differences are apparent even to the casual observer. Some that are not so evident are easily recognized by the experienced soil survey worker. Others are brought to light only by careful laboratory study. These differences are physical, chemical, and biological. They are reflected in the adaptabilities of soils to various crops and in their relative capacities to produce the same crop. It will be recalled, however, that crop growth and distribution are determined by the interaction of several groups of factors, of which those of the soil comprise only one. These other factors affect the crop not only directly, but also indirectly through their influence on the properties of the soil. There is the further complication that soils vary within wide limits as to age. All degrees of degradation of soil particles, therefore, will be found, depending upon the time factor.

SOIL DEVELOPMENT

In the course of their development from rock materials, soils are subjected to processes which effect progressive changes in them. The successive stages in their development have been termed infancy, youth, maturity, and old age. In order that a soil may mature and age, it is necessary that it remain undisturbed over a long period of time. Such a condition obtains only on areas which are practically level and which are not subjected to erosion. In the event that maturity is attained, the nature of the material from which the soil was formed, at least in humid climates, is relatively unimportant. The predominating factors in its development are those of the climate, of which rainfall is the most important. If the topography is rolling, the soil may never develop beyond the stages of infancy or youth, in which event the nature of the rock material from which the soil is being formed is of considerably greater importance than it is in mature soils.

The significance of the climatic factors in soil development was first made apparent by a study of what are known as the *chernozem,* or black soils, of southcentral Russia and western Siberia. It was shown that these soils, which have been developed under an annual rainfall of only 15 to 20 inches, are underlain with a great variety of rocks in different areas, but that, throughout the region, the soils are quite uniform in their characteristics. In the lower zones of most of these soils there has accumulated a layer of concretions of carbonate of lime, no matter what has been the nature of the underlying rock. A study of the climatic factors and the related vegetation shows, without question, that these are the primary agencies that were involved in the development of these soils. Some years later a group of tropical soils, known as *laterites,* was found to be correlated in its distribution with regions of high temperatures and very heavy rainfall. These laterites are characterized by high percentages of the hydrated oxides of iron and aluminum, particularly the latter, and the almost complete absence of aluminosilicates, the silica other than quartz having been entirely leached away.

THE GREAT SOIL GROUPS OF THE UNITED STATES

Soils are classified into orders, suborders, great soil groups, families, series, types, and phases. There are three orders, viz.: zonal, intrazonal, and azonal. The first order includes all those soils having well-defined characteristics which reflect the influence of climate and vegetation. The second order contains those soils that reflect the dominance of some local factor, such as topography, parent material, or age, over the influence of climate and vegetation. The third order embraces all soils having no well-developed characteristics.

Some 36 great soil groups are recognized. In arranging the various series of soils into these groups, consideration is given to the soil profile, the native vegetation, the climate, the natural drainage, and the soil-development processes. Thus the soils of the prairie group are defined as being very dark brown or grayish-brown, and grading through dark brown to lighter-colored parent material at a depth of between 2 and 5 feet. Their native vegetation is tall grass. They were formed under conditions of a temperate, humid climate. They have good drainage, and possess a layer of calcareous material at some depth in the soil profile.

Counterparts of most of the soil groups shown in Table 16 are found in the United States. Undoubtedly, other groups will be added, with more detailed soil surveys of this and other continents.

THE SOIL PROFILE

In the examination of a vertical column of soil, it is found that there are various *horizons,* or layers, having different characteristics. The

TABLE 16

THE GREAT SOIL GROUPS OF THE WORLD (BALDWIN)

Order		Suborder	Great Soil Groups
Zonal soils	Pedocals	Soils of the Cold Zone:	1. Tundra soils
		1. Light-colored soils of arid regions	2. Desert soils
			3. Red desert soils
			4. Sierozem
			5. Brown soils
			6. Reddish-brown soils
		2. Dark-colored soils of the semi-arid, subhumid, and humid grasslands	7. Chestnut soils
			8. Reddish-chestnut soils
			9. Chernozem soils
			10. Prairie soils
			11. Reddish prairie soils
	Pedalfers	3. Soils of the forest-grassland transition	12. Degraded chernozem soils
			13. Noncalcic brown soils
		4. Light-colored podsolized soils of the timbered regions	14. Podsol soils
			15. Brown podsolic soils
			16. Gray-brown podsolic soils
			17. Yellow podsolic soils
		5. Lateritic soils of forested warm-temperate and tropical regions	18. Red podsolic soils
			19. Yellowish-brown lateritic soils
			20. Reddish-brown lateritic soils
			21. Laterite soils
Intrazonal soils		1. Halomorphic (saline and alkali soils of imperfectly drained arid regions and littoral deposits)	1. Solonchak or saline soils
			2. Solonetz soils
			3. Soloth soils
		2. Hydromorphic soils of marshes, swamps, seep areas, and flats	4. Wiesenboden
			5. Alpine meadow soils
			6. Bog soils
			7. Half-bog soils
			8. Planosols
			9. Ground-water podsol soils
			10. Ground-water laterite soils
		3. Calomorphic	11. Brown forest soils
			12. Rendzina soils
Azonal soils			1. Lithosols
			2. Alluvial soils
			3. Sands (dry)

whole series of horizons taken together is known as the *soil profile.* Thus the examination of a typical virgin Miami silt-loam profile shows three horizons, with minor subdivisions of the uppermost, or horizon *A.* The following table is of interest in this connection.

In general, the profiles of mature soils consist of two layers, known as the *A* and *B* horizons. The former is a zone of extraction from which water and acids have removed, in part, the finer particles of soil, the alkalies and alkaline earths, the organic matter, and the oxides of iron and aluminum. No carbonates remain in this horizon of a mature soil. The *B* horizon is a zone of accumulation in which is deposited part of

TABLE 17

Profiles of Two Soil Types (Wheeting)

Horizon		Thickness	Color	Other Characteristics
I*	*A0*	2 in.	Humus	Forest mold
	A1	4 in.	Dark gray	Silt loam, granular
	A2	9 in.	Gray to drab	Silt loam
	B	20 in.	Red-brown	Mottling, heavier texture
	C	Variable	Gray	Compact, contains carbonates
II†	*A0*	2 in.	Humus	Forest mold
	A1	4 in.	Gray-brown	Sandy loam, granular
	A2	10 in.	Yellow-brown	Sandy loam
	B1	20 in.	Red-brown	Heavier, some gravel
	B2	3 in.	Red-brown	Indurated, gravel, carbonates
	C	9 in.	Gray	Unweathered, gravelly drift

* I — Miami silt loam. † II — Bellefontaine loam.

the material that was leached out of the soil above. A third horizon, *C*, consists of unweathered material. The depth to the horizon of accumulation is largely determined by the rainfall. As the amount of rainfall decreases, the zone of deposit of carbonates approaches the surface more and more closely until, in semi-arid and arid regions, it may be only a few inches deep.

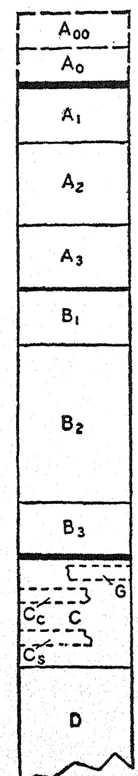
SOIL SURVEYS

It seems desirable for a nation to chart its natural resources, of which the land in relation to its crop-producing qualities is the most important. Most of the states of the United States are cooperating with the Bureau of Soils of the United States Department of Agriculture in a national survey of the soil. The problem is complex: the land area of the United States is estimated at 1,903,000,000 acres; a variety of agencies are involved in the development of the soil; and the natures of the rocks, from which the soil has been and is being formed, are quite variable. Coordinate with the soil survey are the ecological and climatological surveys, which are under the direction of separate governmental bureaus.

It is now recognized that the climate is the most important factor having to do with the development of soil. While the survey worker makes use of the information available from geological surveys, and notes the character of the native vegetation, he maps the soil as it is, the result of agencies of formation and of climatic conditions to which the soil material has been subjected. Of the climatic factors, rainfall is ordinarily the most important. It is apparent, for example, that there would be a vast difference between two soils of granitic rock origin if one of them had been formed under semi-arid conditions and the other had been subjected for thousands of years to high temperatures and the solvent and leaching action of heavy rainfall.

THE CLASSIFICATION OF SOILS

In the classification of soils by survey methods, an attempt is made to arrange them in groups that have in common certain physical prop-



Loose leaves and organic debris, largely undecomposed.

Organic debris partly decomposed or matted; frequently divided into subhorizons.

A dark-colored horizon, containing a relatively high content of organic matter, but mixed with mineral matter. Thick in chernozem and very thin in podsol.

A light-colored horizon, representing the region of maximum leaching (or reduction) where podsolized or solodized. The bleicherde of the podsol. Absent in chernozem, brown soils, sierozem, and some others.

Transitional to *B*, but more like *A* than *B*. Sometimes absent.

Transitional to *B*, but more like *B* than *A*. Sometimes absent.

A deeper-colored (usually) horizon representing the region of maximum alluviation where podsolized or solodized. The ortstein of the podsol and the claypan of the solodized solonetz. In chernozem, brown soils, and sierozem this region has definite structural character, frequently prismatic, but may not have much if any alluviated materials and represents a transition between *A* and *C*. Frequently absent in the intrazonal soils of the humid regions.

Transitional to *C*.

The weathered parent material. Occasionally absent; i.e., soil building may follow weathering so closely that no weathered material that is not included in the solum is found between *B* and *D*. Horizons lettered C_c and C_s represent possible layers of accumulated calcium carbonate or calcium sulfate found in chernozem and other soils.

Any stratum underneath the soil, such as hard rock or a layer of clay or sand, that is not parent material but which may have significance to the overlying soil.

FIG. 8. A hypothetical soil profile. *G* represents the glei layer of the intrazonal soils of the humid region. (Rice.)

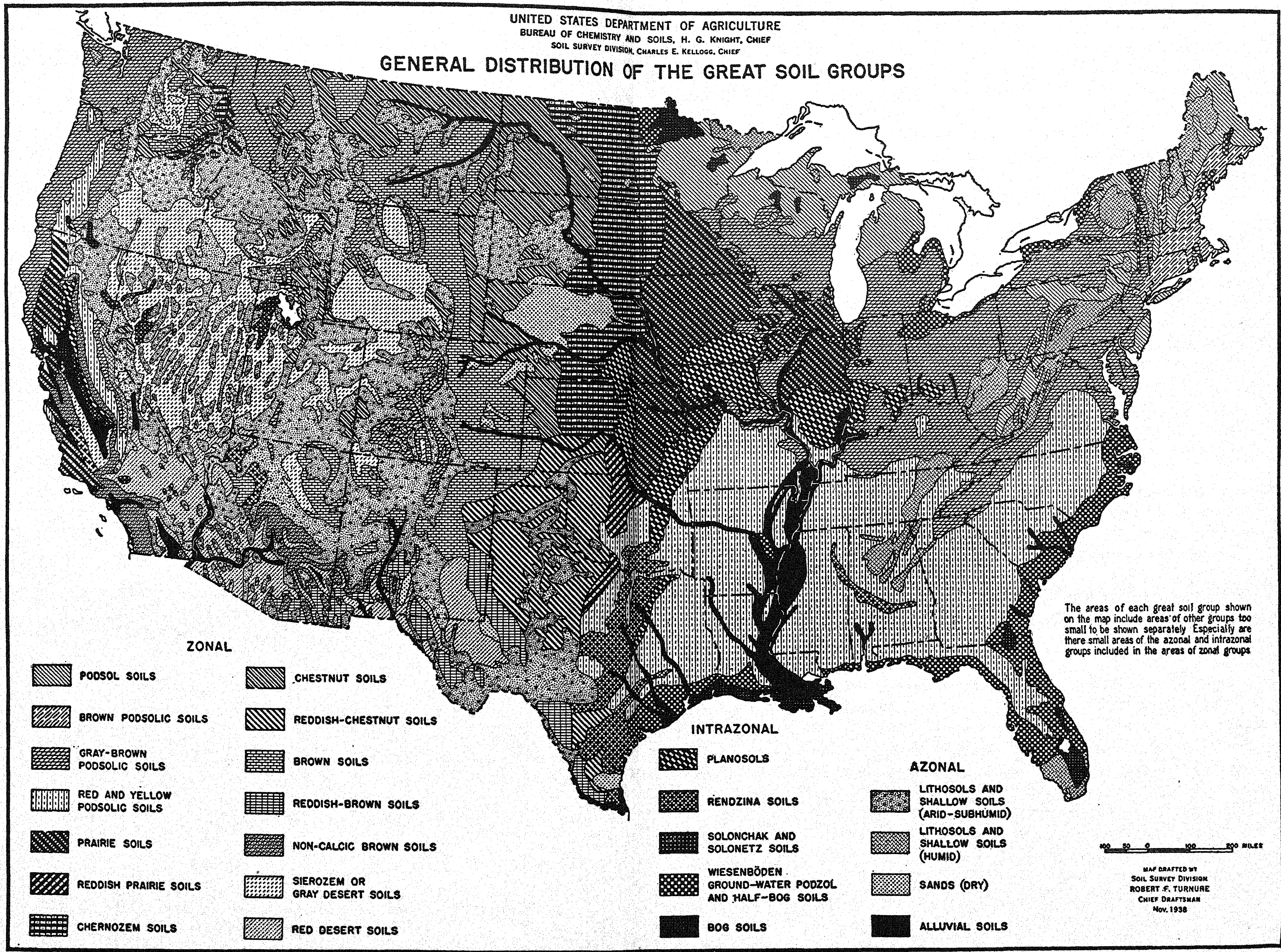


FIG. 9. The great soil groups of the United States.

erties which can be rather easily recognized and differentiated in the field. Soils show considerable variation in the size and arrangement of their constituent particles and in the color of the surface and of the several horizons of the soil profile. Certain simple chemical tests, by which the content of carbonates or the degree of acidity can be estimated, are usable in the field. The natural vegetation is also more or less of a reflection of the physical and chemical properties of the soil as they affect the water and air relationships in the soil and the nature of the soil solution.

The soil-survey worker recognizes that the variations in the characteristics of soils, noted in the field or discovered in the laboratory, have their explanation in differences in the nature of the original rocks from which the soils were derived; in the physical, chemical, and biological agencies operating in their formation and location; in the climatic influences which have surrounded them; and in the length of time which has elapsed since the soils became located in their present positions. For this reason, soils of widely different modes and sources of origin are not grouped together even though they may bear a very close superficial resemblance to each other. The survey worker anticipates that important differences in the properties of such soils will subsequently be discovered by further laboratory tests.

The map presented as Fig. 9 shows the general distribution of the great soil groups in the United States. It is apparent, from a study of this map, that the climatic factors are of primary importance in determining the nature of the soil. It is to be expected that marked changes will be made in the groupings of soils when the detailed surveys have covered a larger part of this country and the relative importance of the various factors involved in soil development is more definitely known.

THE SOIL SERIES

Each of the great soil groups is divided into *series,* all the members of which have, in addition to a common mode of origin, similarity in topography and drainage; in the range of depth, color, structure, and reaction of their surface soils; and in the several horizons of their subsoils. The name applied to a series is usually that of the locality in which it was first recognized and mapped separately. The soils grouped under each series are limited to those that meet the specifications for that series as finally agreed upon by the survey workers.

The Miami series of the Bureau of Soils refers to a group of soils which was first definitely recognized as being distinct from other series when a survey was made of the watershed of the Great Miami River. Their sources of origin were largely the underlying limestone, and the limestone and igneous rock materials carried by the glacier from regions farther north. The soils of this series are defined as being of a gray-brown color with a mottled yellow and gray subsoil. The topography is given as gently rolling and the drainage as fair.

Similarly, the Dekalb series refers to a group of soils, the members of which are residual in origin, are derived from sandstone and shale, and have yellowish-brown surface soils and yellowish subsoils which contain fragments of the parent rocks. The topography of this series is described as hilly and the drainage as very good. This series was first recognized and mapped in Dekalb County, Alabama.

As the survey progresses, new series are named whenever large enough areas of soil are found that have sufficiently distinctive characteristics to justify a separate classification. A few examples of the variations in soils that are used as bases for their classification into series are given in the accompanying table. It is evident that the total number of series will be quite large when the survey of the entire land area of the United States has been accomplished.

TABLE 18

VARIATIONS IN SOME CHARACTERISTICS OF FOUR IMPORTANT SOIL SERIES

Characteristics	Soil 1	Soil 2	Soil 3	Soil 4
Color of soil	Dark brown	Gray-brown	Brown	Brown
Color of subsoil	Yellow-brown	Yellow and gray	Brown-yellow	Red-brown
Reaction	Acid	Not acid	Acid	Not acid
Topography	Nearly level	Gently rolling	Very rolling	Gently rolling
Drainage	Fair to good	Fair	Good	Good
Mode of origin	Glacial	Glacial*	Residual	Residual
Source of origin	Prairie	Limestone	Sandstone†	Limestone
Series name	Carrington	Miami	Dekalb	Hagerstown

* Timbered soils. † Sandstone and shale.

THE SOIL TYPE

The unit of soil classification is the *type*. The series are divided into types on the basis of texture. The word *texture* refers to the relative amounts of the various sizes of particles of which the soil is constituted. Thus the Miami series includes Miami loam, Miami clay, Miami sand, and other types, depending upon their textures. A total of twelve types is possible in any series, provided there is sufficient variation in texture in the soils included in the series. It is seldom, however, that all possible types are found in any one series.

THE SOIL SURVEY IN RELATION TO SOIL MANAGEMENT

Fortunately, in the United States, the Federal Bureau of Soils, co-operating with similar bureaus in the several states, has been able to standardize the methods and nomenclature of soil classification. In some states, only the reconnoissance surveys have been completed. In other states, practically every county has been surveyed in detail. As would be expected, the survey will never be completed for the reason that continued study of the problem makes re-survey on the basis of a better understanding of the soil relationships desirable.

The soil survey is of particular significance in the earlier stages of the agriculture of any state or nation. If it can be completed before farming is begun, an enormous waste of time and funds in trying to grow crops unsuited to the soil and the climate can be avoided. As time goes on, the farmers themselves make what might be considered a reconnoissance survey of the soils of their localities and become somewhat familiar with the crop adaptations and producing capacities. This is of little value to the man who moves into a locality that is new to him and in which the soils are quite different in their characteristics from those to which he has been accustomed.

From the point of view of the experiment station worker and of the soil specialist, the problem is greatly simplified by having at their command a detailed soil survey of the state and an exact knowledge of the characteristics of each series of soils represented. This enables them to know the extent to which each of the various practices which have to do with the improvement of the productive capacities of soils should be emphasized in any given case. Likewise, the farmer, from a consideration of experiment station tests and from the experiences of other farmers with the same type of soil, may be better able to make constructive changes in his soil practices.

However, as agriculture becomes more intensified, the soil is modified to a considerable degree by the farmer to suit his needs. Certain of the soil characteristics which serve as a basis for classification can be very definitely changed. All can be modified in their effects, if the selling prices of crops justify the expense. Thus, the chemical properties of soils can be materially changed through the addition of fertilizers and the growth of clover. The soil reaction can be controlled through the use of sulfur or limestone. Certain physical properties of soils can be markedly modified by the use of tile and by increasing the content of organic matter. Even the climatic factors, which are primarily responsible for differences in soils and which continue to affect their properties, may be regulated by shading, irrigation, and drainage. The soil will eventually be considered more as a mere location on which the plant may stand while it is being "fed," as in China and Japan and, to a lesser extent, in the more intensively cultivated areas of northern Europe.

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[1] A number of words which are descriptive of soil-forming processes have been introduced into the literature within relatively recent years. These include (1) calcification, (2) podsolization, (3) laterization, (4) salinization, and (5) gleization.

Calcification has to do with the redistribution of calcium carbonate in the soil profile, but not with its complete removal. The areas so affected are those of restricted rainfall, varying from 25 inches in the temperate zone to 45 inches in the tropics. Layers of this redeposited calcium carbonate are found at varying distances from the surface.

Podsolization consists of two distinct processes. One of these is an accumulation of leaf litter on the surface of the soil. The other involves the action of water, containing the acids produced in the decomposition of this litter, on the layer of soil immediately below the surface. The net effect is a whitening of the *A* horizon, as a result of the solution and removal of the iron and aluminum, and an accumulation of these dissolved products and of finely divided clay, in the *B* horizon.

Laterization is the name applied to the progressive hydrolysis of siliceous minerals as a result of which the soil comes to be made up mostly of the hydrated oxides of iron and aluminum. Lateritic soils are formed under conditions of relatively heavy rainfall and high temperatures. They are yellow to red in color, are very low in mineral nutrients, and have an abnormally high capacity to fix any phosphoric acid fertilizers that may be applied.

Salinization has to do with the formation and accumulation of soluble salts under conditions of limited rainfall and high rates of evaporation of water. These salts are mostly sulfates, chlorides and carbonates of sodium, potassium, calcium and magnesium. If the salts are largely sodium and potassium carbonates, they form what is known as black alkali.

Gleization is the term applied to the process by which bluish or greenish waterlogged soil horizons are formed under bogs and swamps, where peat deposits accumulate. The color is due to the reduced state of the compounds of iron and manganese.

CHAPTER V

CHEMICAL COMPOSITION OF SOILS

The rocks from which soils are formed differ considerably in their mineralogical and chemical composition. Even the rocks that belong to the same class show wide variations in composition. Limestone may be almost pure calcium carbonate; it may contain magnesium carbonate in as high a percentage as is required for the dolomitic ratio ($CaCO_3MgCO_3$); or it may consist in large part of impurities such as sand and clay. The igneous rocks are commonly divided into three groups, namely: acidic, intermediate, and basic, depending on their percentage content of silica. This may vary from 40, in basalts, to nearly twice that amount in granites. Sandstones and shales differ markedly in their composition, depending on the conditions under which they were deposited.

In the process of soil development, the mineral and other compounds in the soil are decomposed as a result of the solvent action of water and of the various acids and salts that may be dissolved in it. At any given time, the soil may contain products representing all the stages from the original rocks and their minerals to the end products of their decomposition. Since soils have their origin largely in rocks, it might be expected that mineralogical analysis would provide a clue to the nature of the rock or rocks from which they were formed.

MINERALOGICAL COMPOSITION OF SOILS

Considering the great differences in the mineral composition of the various classes of rocks, it is somewhat surprising to find that most of the common rock-forming minerals are rather generally distributed in soils. This is shown in Table 19, the data for which were secured from the mineralogical analyses of twenty-five samples of soil selected from as many different and widely separated localities in the United States. But, while the distribution of these minerals is rather general, it has been shown that some soils contain certain of them in much larger amounts than do others. Two facts of especial significance are apparent from these analyses: one is the abundance of quartz; and the other, the relative scarcity of apatite, the only phosphate mineral that the soil contains.

TABLE 19

PRIMARY MINERALS IN TWENTY-FIVE SOILS (McCAUGHEY)

Minerals	Oxides Contained	Present*	Abundant*
Quartz	Si	25	25
Hornblende	Ca-Mg-Fe-Si	23	12
Orthoclase	K-Al-Si	20	14
Microcline	K-Al-Si	20	10
Epidote	Ca-Fe-Al-Si-H	24	8
Biotite	K-Mg-Fe-Al-Si-H	21	8
Muscovite	K-Al-Si-H	20	6
Zircon	Zr-Si	22	1
Chlorite	Mg-Fe-Al-Si-H	21	2
Tourmaline	Na-Al-B-Si-H	21	1
Rutile	Ti	17	0
Plagioclase	Na-Ca-Al-Si	13	5
Apatite	Ca-P-(F and Cl)	12	0

* Number of soils in which the minerals were present and abundant, respectively.

EFFECTS OF WEATHERING ON MINERALS

In the processes of weathering and leaching in humid climates, any soluble compounds that are formed are carried away in the drainage waters while relatively insoluble residues accumulate to form soil. Thus, a soil of limestone origin may contain no carbonates. Soils of sandstone and shale origin may differ very little in composition from the original rocks. A soil of igneous origin tends to lose its base-forming elements as bicarbonates. As a result, silicon, aluminum, and iron — in the forms of their oxides, or in silicate combinations of these oxides containing relatively small percentages of the elements sodium, potassium, calcium, and magnesium — tend to constitute the major

TABLE 20

PERCENTAGE COMPOSITION OF GRANITE AND ITS SOLUTION PRODUCT (HEADDEN)

Oxides	Granite	Dissolved Material*	Order of Solution
SiO_2	65.76	40.72	5
Al_2O_3	19.29	2.70	6
Fe_2O_3	Trace	0.31	..
CaO	0.314	10.24	1
MgO	0.029	0.77	2
K_2O	11.60	10.97	4
Na_2O	2.73	5.25	3
Ignition	.....	16.37	..

* This product resulted from washing powdered granite with eighteen successive additions of water kept agitated by a stream of air to which some CO_2 had been added.

portion of most soils in humid regions. Even the silicon, especially that in the silicate form, tends to disappear in hot climates of very high rainfall, leaving a laterite soil which is composed almost entirely of the hydrated oxides of aluminum and iron, particularly of the former. The relative rates of solution of the several elements in a granite are shown in Table 20.

It will be noted that the order of solubility of the elements is calcium, magnesium, sodium, potassium, silicon, and aluminum, respectively. It is evident that the silica is somewhat soluble and that the remaining residue tends to contain an increasing percentage of alumina.

In contrast with the soils of humid climates are those that are the result of weathering under arid conditions. Under these circumstances, there may be little difference between the percentage chemical composition of the soil and the rock from which it was formed. In the absence of any large amount of rainfall, little may be leached from the soil in the process of its development. While there is always some decomposition of the mineral constituents, the soil suffers little or no loss of its mineral elements unless leaching takes place.

It is to be expected, therefore, that the analyses of soils for the total amounts of the elements contained in them will show wide variations, depending not only on the nature of the rock from which they were formed but also on their age and the extent to which they have been subjected to the leaching action of water. Even in regions having the same rainfall, no two soils have the same composition since their rock and mineral origin and the combination of forces operating in their formation and alteration, including the element of time, are never identical.

INORGANIC COMPOSITION OF REPRESENTATIVE AMERICAN SOILS

The elements that make up the major portion of soils in humid climates are of relatively little importance in plant economy. This is because they are present in such large amounts, as compared with any possible need of the plant for them, that, even though they occur in relatively insoluble forms, it is seldom that a deficiency of any one of them becomes a limiting factor in crop production. On the other hand, the elements that tend to be most readily leached from the soil are the ones that are also required in considerable amounts by plants. The problem is further complicated by the fact that the relative availabilities of the several essential plant elements in a series of soils are not necessarily in proportion to the quantities of these elements which the soils contain. Nevertheless, it is a matter of considerable interest to

TABLE 21

PERCENTAGE INORGANIC COMPOSITION OF REPRESENTATIVE AMERICAN SOILS (ROBINSON*)

Series and Type	State	Depth	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3
Norfolk sand[1]	S. C.	8 in.	94.81	0.51	1.42	0.60	0.02	0.19	0.01	0.08	0.12	0.10	0.08
Ruston fine sandy loam[1]	La.	6 "	95.51	0.36	1.70	0.68	0.02	0.12	0.00	0.16	0.04	0.04	0.23
Durham sandy loam[2]	N. C.	10 "	80.79	0.53	10.55	1.61	0.02	0.89	0.19	0.96	0.87	0.12	0.06
Louisa loam[2]	Va.	12 "	84.58	1.51	5.54	3.30	0.05	0.21	0.25	0.74	0.14	0.12	0.15
Sassafras silt loam[2]	Md.	8 "	82.88	1.09	7.49	2.25	0.04	0.41	0.36	1.87	0.90	0.15	0.05
Gloucester stony loam[3]	N. H.	8 "	65.68	0.79	14.15	5.67	0.07	1.36	0.83	2.16	1.39	0.11	0.03
Clermont silt loam[3]	Ohio	6 "	75.30	....	10.27	6.34	....	0.77	0.95	1.84	....	0.15	....
Marshall silt loam[3]	Mo.	15 "	75.61	0.71	9.67	3.54	0.12	1.08	0.77	2.28	1.03	0.22	0.17
Memphis silt loam[3]	Miss.	6 "	81.13	0.78	8.52	2.92	0.03	0.31	0.39	1.78	0.52	0.08	0.03
Volusia silt loam[3]	N. Y.	8 "	75.12	0.68	10.49	4.13	0.02	0.49	0.48	1.40	0.90	0.18	0.09
Miami silty clay loam[3]	Ind.	10 "	77.79	0.91	9.74	2.68	0.08	0.61	0.62	2.18	1.09	0.29	0.03
Wabash silt loam[3]	Neb.	15 "	72.37	0.58	12.23	3.35	0.10	1.07	0.93	2.35	1.20	0.14	0.16
Carrington loam[3]	Wis.	12 "	77.28	0.53	8.93	2.89	0.06	0.84	0.56	1.35	1.15	0.14	0.10
Dekalb silt loam[4]	W.Va.	7 "	.....	1.20	8.12	2.77	0.31	0.15	0.37	1.45	....	0.07	0.16
Clarkesville silt loam[4]	Ky.	10 "	81.85	1.37	7.35	2.79	0.15	0.29	0.23	1.36	0.95	0.08	0.08
Dectaur clay loam[5]	Ala.	4 "	79.35	1.15	8.89	4.44	0.07	0.63	0.39	0.67	0.24	0.18	0.23
Hagerstown loam[5]	Pa.	8 "	70.99	1.01	11.39	4.23	0.18	0.93	1.08	2.71	0.82	0.19	0.34
Cahaba fine sandy loam[6]	Ga.	12 "	91.39	0.52	3.72	0.97	0.07	0.21	0.09	0.90	0.12	0.06	0.06
Colorado sand[7]	Colo.	14 "	78.85	0.32	9.68	2.72	0.03	0.94	0.72	2.31	2.02	0.11	0.07
Oswego silt loam[7]	Kan.	14 "	71.38	0.68	12.29	3.63	0.05	1.09	0.36	2.28	1.14	0.10	0.12
Richfield clay loam[7]	Tex.	10 "	79.64	....	8.27	2.74	....	0.63	0.87	1.83	1.12	0.10	....
Palouse silt loam[8]	Idaho	12 "	69.60	....	13.62	5.30	0.00	2.47	1.41	1.99	2.91	0.20	....
Stockton clay adobe[9]	Calif.	38 "	63.52	1.21	14.34	7.98	0.16	2.34	1.81	0.78	1.68	....	....
Highest percentages	......	......	95.51	1.51	14.34	7.98	0.31	2.47	1.81	3.96	2.91	0.29	0.34
Lowest percentages	......	......	63.52	0.32	1.42	0.60	0.00	0.12	0.00	0.08	0.04	0.04	0.03

* A few of these analyses were taken from other sources.

[1] Coastal plain region. [2] Piedmont Plateau region. [3] Glacial and loessial region. [4] Appalachian Mountain and Plateau region. [5] Limestone valleys and uplands region. [6] River flood plain region. [7] Great Plains region. [8] Northwest intermountain region. [9] Pacific coast region.

know the exact composition of soils of various types, before proceeding to a discussion of their crop-producing qualities.

Table 21 contains data from analysis of twenty-three typical American soils, chosen from as many states and each representing a different series. The textures of the soils vary from sands to clays. It may be well to point out that no one sample can be said to be representative of the soils of the state from which it was selected, but only of the type from which it was chosen. Even different samples chosen from any one type may vary considerably in their chemical composition, depending upon the history of the areas from which they were taken.

RARER ELEMENTS IN SOILS

In addition to the elements whose oxides are listed in Table 21, soils contain varying amounts of others which may or may not be of any importance in plant economy. The highest and lowest percentages of the oxides of some of these elements that were found in fourteen samples of soil, representing as many series, are given in Table 22.

TABLE 22

PERCENTAGE CONTENTS OF OXIDES OF RARER ELEMENTS IN SOILS (ROBINSON)

Element	Oxide	Highest	Lowest
Chromium	Cr_2O_3	0.018	Trace
Vanadium	V_2O_5	0.08	0.01
Zirconium	ZrO_2	0.08	0.003
Barium	BaO	0.287	0.004
Strontium	SrO	0.11	0.01
Lithium	Li_2O	Present	Present
Rubidium	Rb_2O	0.01	Trace

Analyses have shown the presence, in practically all soils, of measurable amounts of arsenic, zinc, boron, copper, and other elements. Since little is known concerning their functions, if any, in plants, and because of the difficulties involved in their determination in the small quantities in which they are present, there is little information concerning their distribution in either soils or plants. It is possible that the lack of productiveness of some soils for certain crops, and the exceptional productivity of others for the same crops, may have their explanation, in part, in the absence or presence of one or more of these elements. To date, most attention has been given to the elements sodium, potassium, calcium, magnesium, iron, aluminum, manganese, phosphorus, sulfur, and silicon in soil and plant economy. However, boron, copper, zinc, molybdenum, and certain other elements are receiving much more consideration than formerly. There is increasing likelihood of need for them, now that the virgin supplies of organic matter and the mineral elements which were contained in them, have largely disappeared.

SOILS OF EXCEPTIONAL CHEMICAL COMPOSITION

Some soils have been shown to be exceptional in their chemical composition. Certain beach sands have been found to contain more than

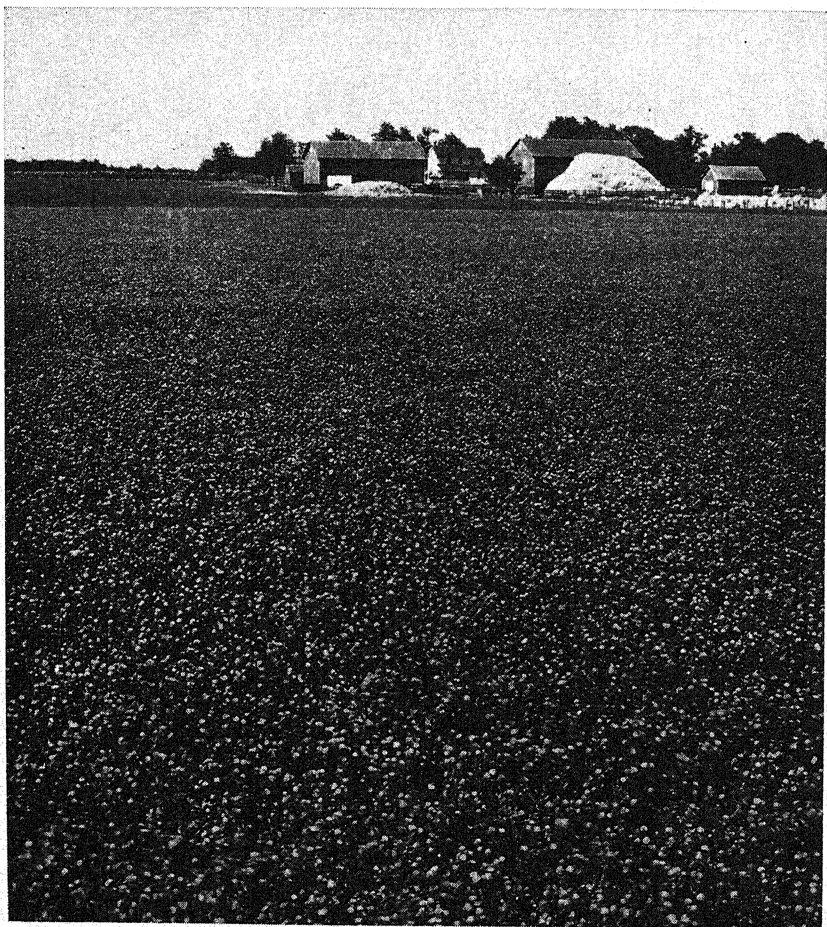

FIG. 10. Clover is an excellent indicator plant for determining whether the soil is well supplied with mineral nutrients. As long as this crop thrives, all is well.

98 per cent silica. This limits the amounts of other soil compounds to very small percentages. The phosphoric acid (P_2O_5) content of the soils of the Trenton area, in Kentucky, is reported to average over 1 per cent. In no case is the amount of phosphoric acid found to be less than 0.3 per cent, and in some places it is as high as 2.65 per cent. The sulfur trioxide content of certain Oregon soils has been shown to be less than 0.04 per cent. Young soils of limestone origin frequently contain sufficient calcium carbonate to effervesce copiously when treated with hydrochloric acid. Some unproductive black soils of northern Indiana are found to be nearly 80 per cent organic matter, while their potash (K_2O) content does not exceed 0.2 per cent.

Soils of arid regions are frequently covered with deposits of various soluble salts that have been derived from the decomposition of minerals. Certain Hawaiian soils contain as much as 10 per cent manganese oxide. These last are of especial interest by reason of the fact that they contain so little soluble iron that pineapples grown on them develop chlorosis unless given an application of a solution of some ferrous salt.

CHEMICAL COMPOSITION OF SOILS BY HORIZONS

Analyses of soils have long been reported in terms of soil and subsoil, the soil being considered as the surface 6⅔ inches, the subsoil being that part of the soil body below this depth. A more logical presentation of such analyses would be on a horizon basis. Only relatively few analyses have been reported on this basis. Of these, a typical example is shown in Table 23.

TABLE 23

CHEMICAL COMPOSITION* OF VIRGIN COLLINGTON LOAM SOIL (LIPMAN)

Horizon	Depth†	N	P	Ca	Mg	Mn	SiO_2	Fe	Al
A_0	3	0.91	0.09	0.33	0.29	0.23	60.0	2.23	1.74
A_1	9	0.11	0.07	0.18	0.27	0.05	84.1	2.56	2.69
A_2	23	0.03	0.04	0.20	0.31	0.10	85.4	2.96	3.07
B_1	18	0.02	0.06	0.18	0.42	0.13	79.6	4.18	3.75
B_2	26	0.01	0.06	0.15	0.46	0.16	79.5	4.60	3.37
C_1	13	0.01	0.06	0.16	0.50	0.12	80.5	5.15	2.65
C_2	..	0.01	0.03	0.15	0.41	0.14	84.8	4.73	1.59

* In terms of elements, except for silicon, which is reported as SiO_2. Figures are percentages of air-dry soil.

† Depth in centimeters (1 centimeter = 0.4 inch).

Collington soils belong to the podsolic group. The analysis shows a tendency toward an accumulation of nitrogen, phosphorus, and silicon in the *A* horizon, and of magnesium, manganese, iron, and aluminum in the *B* horizon. Potassium percentages were not reported, but there was probably about 1 per cent of this element in the *A* horizon and somewhat more than this in the *B* horizon.

ORGANIC MATTER IN SOILS

In addition to inorganic materials, soils contain organic matter in amounts varying from as little as 1 per cent to as much as 80 per cent of their mass. This organic matter is largely plant residues and contains the elements that are found in plants, subject to whatever losses may have occurred through decomposition and leaching. Such amounts of the inorganic oxides as are contained in organic matter are included in the percentages reported in Table 21, showing the inorganic composition of soils. But organic matter also contains nitrogen, in protein form, which is yielded up as nitrate for plant use when this protein material undergoes decomposition as a result of the action of soil microorganisms. The quantity of this element in inorganic soils, in plant remains, ordinarily ranges from about 0.5 per cent to 0.1 per cent. In muck and peat, the organic nitrogen may amount to as much as 4 per cent of the total mass of the soil. Further consideration of this element and of the organic matter which contains it will be reserved until later.

The figures previously given on the composition of soils represent the total amounts present in them. They provide no very definite clue to the quantities of these elements which would be available for plant use in the immediate future. A high content of any element may actually mean that this element is present in a form that is very resistant to weathering and to the solvent action of the soil water. However, if one soil contains twice as much potassium as another soil of the same physical characteristics, it seems reasonable to believe that the former can be made to yield up more of this element to plants than the latter, although not necessarily in the ratio of 2 to 1. If the soil's content of phosphorus is extremely low, little can be expected from efforts designed to make this phosphorus available for crop use. Similarly, studies of the nitrogen content of soils are of indirect value in determining their relative need for this element.

MODERN METHODS OF SOIL TESTING

It was early recognized that the data obtained by analyses of soils for their total contents of the several nutrient elements failed to yield the answer to their immediate needs for satisfactory crop production. This led to the study of methods designed to simulate the solvent action of plant roots. Among the several procedures proposed were those in which use was made of dilute solutions of carbonic, citric, oxalic, nitric, and sulfuric acids. After many years of study of this problem, fairly standard methods have been developed. These methods call for the use of highly buffered dilute-acid solutions for extracting the available phosphorus and for the use of salt solutions for replacing what is known as the *exchangeable* potassium, calcium, magnesium, and other nutrient cations in the soil complex. The two extracting solutions may be combined in one. This is made by dissolving 30 milliliters of glacial acetic acid and 100 grams of sodium acetate in 1 liter of water. A teaspoonful of soil is placed in a small beaker containing 10 milliliters of this solution. The mixture is stirred for 1 minute and filtered. The resulting clear solution is tested colorimetrically for the elements in question.

PLANT-TISSUE TESTING

The plant gives the final answer to the adequacy of the nutrient supply in the soil in which it is growing. If the plant grows luxuriantly, adequate amounts of the mineral elements must have been delivered up by the soil. If it does poorly, a nutrient deficiency is a possible cause. Examinations of plant tissues have revealed that the sap of each species of plant maintains a fairly constant ratio of the soil nutrients, under optimum conditions of growth. Any departure from this normal ratio indicates an excess or deficiency, as the case may be. It seems probable that this method of diagnosing soil deficiencies will come into much greater use than it now enjoys. Its greatest weakness lies in the fact that the plant must be grown before its tissues can be tested, whereas the soil can be examined before the seeds are sown.

SOIL TESTING AS A GUIDE TO PRACTICE

If the analysis of a soil is to be of any considerable value as a guide to practice, the sample must be chosen by or under the direction of someone who appreciates the limitations of the quantitative method of study. Soils vary in their chemical composition from point to point in the same field. Their composition changes with depth. Quite often the subsoil contains carbonate of lime, which may be entirely absent from the surface soil. For this reason, a sample for examination should be chosen to some standard depth and in such a manner as to be representative of the area sampled. The soil survey worker chooses his samples according to soil type and at a depth depending upon the natural stratification of the soil material. For practical purposes, it is probably better to choose one set of samples to plow depth and a second set from a corresponding depth immediately beneath the first samples. Thin slices of soil, taken with a spade or an auger at about a dozen different points from each soil type, make a satisfactory composite sample for laboratory study. The best time to select such samples is in the late fall.

By reason of the large amount of analytical work which has been done on soils and from their systematic classification by the survey method, it is possible for the chemist who is familiar with the data now available and with their significance in relation to plant growth, if he knows the location of the farm from which the sample was selected, to judge the quality and anticipate the needs of the soil from a more or less superficial examination of it. This is especially true in those states in which systematic field tests of soil-management practices have been and are being made. Under these conditions, the acidity test, the color, the feel of the soil between the thumb and finger, and a knowledge concerning the crops to be grown constitute for the soil chemist a fairly reliable guide to the system of soil management which will meet the requirements for larger yields.

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CHAPTER VI

SOME BIOLOGICAL PROCESSES IN SOILS

Early in the history of the study of soils it was found that their productive capacity is often more or less directly related to the amount of organic matter which they contain. Later it was shown that organic materials serve as food for the growth and energy of large numbers of microscopic organisms which inhabit the soil. As time went on and the methods of study of these minute organisms became more refined, it was discovered that most of them are very simple forms of plant life which apparently function in the preparation of soil materials for the use of the higher plants. Biologists succeeded in isolating from soils members of five groups: bacteria, actinomycetes, algae, fungi, and protozoa; in studying them in pure cultures; and in determining somewhat definitely their growth requirements and the specific functions which they perform.

METHODS OF STUDY OF THE SOIL FLORA

As a preliminary to any systematic classification of the soil flora, it was necessary to study various kinds and qualities of media in order to determine which ones are best suited to the purposes of isolating the different classes of organisms from the soil. Investigation has revealed the fact that an enormous number of species and strains of bacteria and fungi are to be found in the soil. No one artificial medium can be chosen which will meet the requirements of both groups or even of all the members of either group.

Bacteriologists have approached the study of the soil flora from several points of view. One method is that of studying in detail some bacterial process which is known to take place in soils. In this mode of attack, the medium is so chosen as to favor the activities of the bacteria that function in the process. By a series of selective cultures, the causal organism or group of organisms is more or less segregated and its isolation is finally accomplished. When these pure cultures have been secured, the organisms are studied in detail as to their morphology and physiology and their requirements for optimum growth. It was by a process of this type that the bacteria which produce nitrates were first isolated from soils.

A second method is that of making use of a medium which meets the requirements of a considerable range of soil organisms. The colonies that result from pouring plates of such a medium which have been seeded with soil suspensions are studied individually, pure cultures are produced from them, and an attempt is made at a systematic classification on the basis of their morphological and physiological characteristics. By varying the composition, reaction, and conditions as to aeration of the medium, the various groups of bacteria and fungi may be isolated and studied.

In a third and somewhat superficial method of study of the soil flora, counts are made of the number of colonies which will develop on Petri dishes, containing a suitable medium, from the use of a known quantity of a suspension of soil in sterile water.

A microbiological census of the soil shows that it ordinarily contains millions of microbes per gram. Of these, probably 90 per cent will be bacteria, 9 per cent actinomycetes, and 1 per cent algae, molds, and protozoa. For any given class of soils, such as sands, silt loams, or clays, the total microbial population will be closely related to the soil's content of organic matter since this constitutes the primary food of most soil microbes.

Any system of soil management which increases the soil's content of organic matter, proportionally increases its microbial population, with all the advantages that accrue as a result of their activities. That is one important reason for having a cropping system which maintains a high content of organic matter in the soil. Some idea of the effect of the cropping system on the current supply of microbial food can be gained from the examination of the following table.

TABLE 24

Cropping System in Relation to Microbial Food Supply (Albrecht)

Crops and Their Disposal	Organic Matter in Soil	
	Gain*	Loss*
Rye as green manure, followed by fallow	......	14,400
Corn, wheat, clover — crops removed	......	800
Corn, wheat, clover — manure returned	3,200	......
Grass sod — clipped but nothing removed	10,000	......
Alfalfa continuously — crops removed	10,400	......

* Gain or loss of organic matter in pounds per acre of plowed soil, over a period of seventeen years.

CLASSIFICATION OF THE SOIL FLORA

As previously indicated, the soil flora is made up of five groups of organisms: bacteria, actinomycetes, algae, fungi, and protozoa. These groups are composed of large numbers of distinct species having different morphological and physiological characteristics. The functions of certain of these species are well known. The importance of others in soil and plant economy is unknown. By the usual method of counting on plates, it has been found that a gram of ordinary surface soil may contain 1 to 10 million bacteria. In addition, there are known to exist in the soil large numbers of other organisms which require for isolation the use of special media suited to their needs, or incubation under anaerobic conditions. Thus the ordinary counts of soil organisms do not include the nodule bacteria of legumes; the non-symbiotic, nitrogen-fixing bacteria; the nitrite- and nitrate-producing bacteria; the anaerobic bacteria; nor any of the algae or fungi.

Ordinarily, bacteria comprise about 90 per cent of the soil flora, if the reaction of the soil is approximately neutral. If the soil is somewhat acid and contains considerable organic matter, the fungi may predominate. Algae are not present in large numbers except under conditions of abundant moisture. Their greatest development is in greenhouses, in shady locations, and in soils that are kept continuously moist.

Of the bacteria, the non-spore-forming short rods are usually the most abundant. Under certain conditions, particularly following applications of manure, the filamentous actinomycetes may predominate. Relatively, micrococci are usually not very abundant. When soils are given special treatments in the laboratory that are favorable to any one group of bacteria, there may be a very rapid increase in the numbers of that group. This is what is attempted when peat is employed as a culture medium for the nodule bacteria which are to be used for inoculating purposes.

The soil also contains considerable numbers of protozoa. It is believed that these protozoa play an important part in the cycle of changes which occur in the decomposition of organic matter, particularly in the rotting of manure. Following a period of rapid bacterial multiplication, and in the presence of suitable moisture conditions in the manure heap, the protozoa probably consume large numbers of bacteria and rapidly increase in number. Later the bodies of dead protozoa are decomposed, and new groups of bacteria and actinomycetes gain the ascendency.

THE MASS OF BACTERIAL CELLS IN SOILS

A gram of rich surface soil may contain as many as 100 million bacteria. Also contained in it will be large numbers of fungi and algae and 10 to 25 or more thousand much larger protozoa. An ordinary rod-shaped bacterial cell has a diameter of about 1 micron and a length that is approximately twice its diameter. Assuming that bacterial bodies have a specific gravity equal to that of water, the weight of bacteria in an acre of soil to plow depth would approximate 315 pounds. If to this is added the weight of the other microorganisms in the soil, the total weight might be twice this amount, or 630 pounds an acre. If 80 per cent of their mass is water, the total dry weight of microorganisms in the acre of soil would amount to 125 pounds. There is some evidence in favor of the belief that the number of microorganisms in the soil is much larger than is indicated above, especially in manured soils. Of interest in this connection is the fact that it has been estimated that 20 to 25 per cent of the dry weight of animal excrements is made up of bacteria.

The chemical composition of bacterial bodies is of considerable interest. The following table gives the content of nitrogen and mineral elements in the cells of two important species of bacteria that are common to most productive soils.

TABLE 25

PERCENTAGE COMPOSITION OF BACTERIA* (STOKLASA)

Material	*Azotobacter chroococcum*	*Bacterium mycoides*
N	11.30	10.84
P_2O_5	4.90	4.07
SO_3	0.29	0.49
K_2O	2.41	2.27
Na_2O	0.07	0.12
MgO	0.82	0.48
CaO	0.34	0.05
Fe_2O_3	0.08	....

* On dry-weight basis.

IMPORTANT FUNCTIONS OF SOIL BACTERIA

Plant and animal substances must undergo decay before the elements that are contained in them can be used again by plants. In this process, these substances undergo hydrolysis and oxidation, with perhaps intervening stages of reduction. The end products of decomposition, under favorable conditions as to moisture and oxygen supply, are the oxides of the elements contained in plants, of which water, carbon dioxide, and nitric and sulfuric acids are examples. The soil contains important species of anaerobic bacteria which find favorable conditions for growth in those zones in which the oxygen supply has been reduced by the action of aerobic bacteria, or in those portions of the soil in which the pore space is filled with carbon dioxide or water. Certain species of bacteria are known to possess the power of taking carbon and nitrogen from the atmosphere, the latter element being of particular significance in connection with the growth of higher plants.

An examination of the organic matter of soils will ordinarily show a great variety of products ranging from those contained in the original material to the end products of bacterial action. Of the intermediate group may be mentioned the simple sugars and the alcohols, aldehydes, and acids derived from the hydrolysis and oxidation of the carbohydrate and oil substances in plants; the various amino acids which have their origin in proteins; and the more complex materials which collectively are ordinarly called humus.

Of the various bacterial processes which take place in soils, those of nitrification, nitrogen fixation, and mineralization are probably of most significance in connection with the management of soils in relation to the growth of plants. These processes are somewhat complex and are still fruitful fields of investigation, with reference to both the physiology and morphology of the bacteria which are responsible for them and the conditions that are most favorable to their accomplishment.

THE NATURE OF BACTERIAL PROCESSES

It is difficult to conceive of the mechanism by which insoluble materials may be attacked by bacteria unless it be by some agency that operates on the outside of their cell walls. The explanation that is given of such phenomena is that the bacterial cells excrete enzymes which serve to render these products soluble, after which they may diffuse through the cell walls and serve as food for growth and energy of the bacteria. The process is similar to that which occurs in the digestive tract of animal bodies, where food materials are digested and then diffuse into the blood vessels. After these products have been utilized by the animal body, excretory products, such as water, carbon dioxide, urea, and other simplified compounds, are given off by the skin, lungs, and kidneys, or are excreted with the feces. Similarly, bacterial cells bring about the solubilization and decomposition of organic materials, the final oxidation products from which are then utilized by growing plants and reconstructed into plant tissue.

THE SOURCE OF THE NITROGEN OF PLANTS

Liebig, in 1840, was of the opinion that the nitrogen of plants came from the ammonia of the atmosphere. The nitrogen of organic residues in soils was thought to be of use to plants only after its liberation as ammonia in the process of decay. The supplemental source of nitrogen to take the place of that removed in crops, or lost from the soil by other means, was thought to be the ammonia which is contained in the rainwater and is brought back to the soil by that means. It was later shown by Lawes and Gilbert that the total amount of combined nitrogen in the rainfall at Rothamsted, England, averages only 3 to 5 pounds an acre annually, a quantity which is entirely too small to compensate for the losses in crops and drainage. Subsequent analyses of the rainwater at other experiment stations have confirmed this conclusion.

It was finally proved that the nitrogen of plant residues in the soil is made available to succeeding crops through the action of several groups of bacteria, nitric acid being an end product of the activities of these organisms. The nitric acid reacts with the basic elements in soils to produce nitrates. More detailed studies of the processes involved in the change of protein nitrogen to nitrate show that at least three distinct groups of bacteria are instrumental in bringing this about. The first of these has to do with the production of ammonia; the second, with its change to nitrous acid; and the third, with the further oxidation of the resulting nitrites to nitrates.

THE PROCESS OF NITRIFICATION

The decomposition of protein substances is not the result of the activities of any one group of soil organisms, but is accomplished by many different species of bacteria, actinomycetes, fungi, and protozoa. The process may be either aerobic or anaerobic, depending upon the conditions that obtain. The first products of protein decomposition are amino acids. These are normally broken down to form ammonia, carbon dioxide, and water. Inorganic elements like sulfur are liberated as oxides. Under anaerobic conditions, free nitrogen, methane, and hydrogen sulfide may be formed. If the organic matter contains less than 10 per cent protein (1.5 per cent nitrogen), all the ammonia liberated during the earlier period of its decay will be utilized by the microorganisms effecting its decomposition and none will be liberated for crop use.

The steps in the process of nitrification have been carefully worked out. While methods for the production of nitrates had long been known, and saltpeter plantations had for many years been subsidized by the various governments as a means of securing adequate amounts of nitrates for use in the manufacture of gunpowder, the fact that the process is a bacterial one was not discovered until 1877, when it was demonstrated by Schloesing and Muntz, in connection with some studies of the purification of sewage. Their discovery was followed by a considerable amount of investigational work on the subject. However, pure cultures of the bacteria that are responsible for the process of changing ammonia to nitrates were not secured until 1890, when Winogradsky succeeded in isolating them on media made of silica gel, containing only inorganic constituents. This discovery is of especial significance since it demonstrates that these bacteria can utilize the carbon dioxide of the atmosphere, a function which was previously believed to be confined to green plants.

Three species of bacteria are concerned in changing ammonia to nitrates. The first step is the production of nitrous acid, which reacts with the basic elements in the soil to form nitrites. Two species of bacteria, *Nitrosomonas* and *Nitrosococcus,* are able to bring this about. The third species, *Nitrobacter*, changes the nitrites to nitrates. Investigation has shown that the last-named species is not able to function until the nitrites have been produced as a result of the activities of one or the other of the ammonia-oxidizing species of bacteria. Some difficulty is experienced in growing any of these bacteria in the laboratory in media containing soluble organic matter but, apparently, no injury results from its presence in the soil.

THE RATE OF NITRATE PRODUCTION IN SOILS

A considerable number of factors are involved in determining the rate at which nitrogen in the form of organic residues in soils will be changed to nitrates. One of the difficulties involved in studying this process, as it occurs in a soil, lies in the fact that nitrate formation may proceed more rapidly than the accumulation of nitrates would indicate. Bacteria, as well as higher plants, require soluble nitrogen for growth. The nitrate accumulated in soils represents what is produced in excess of the requirements of the bacterial and plant population of those soils.

Keeping in mind the limitations of studies which measure the quantities of nitrates that are present in soils, it is found that the rate of nitrate accumulation is determined largely by the recentness of the origin of the organic materials, their ratios of carbon to nitrogen, the temperature and water content of the soil, and the reaction of the soil solution. A good corn soil may contain 6000 pounds of nitrogen an acre to plow depth. A 100-bushel crop of corn requires about 150 pounds of nitrogen in the nitrate form. Yet it is seldom possible to produce that amount of corn on an acre unless the nitrogen of the soil has been supplemented by manure, a heavy growth of clover, or commercial carriers of soluble nitrogen.

Unless the first step in the process of nitrification, namely, the production of ammonia, has been accomplished, the others do not take place. If the soil does not contain carbonate of lime or some other basic compound to neutralize the nitrous acid produced, there may be somewhat of an accumulation of ammonia. This may also occur if the soils are waterlogged or if for any other reason anaerobic conditions obtain.

THE FIXATION OF NITROGEN BY LEGUME BACTERIA

It was early recognized that, if the nitrogen in the organic residues in soils is supplemented only by that which comes down in combined form in the rainfall, the continued removal of crops and the losses which occur through leaching would result in the exhaustion of the supply of this element in the soil. The good effects of legumes on the other crops in the rotation had long been known. The presence of nodules on their roots had also been observed and some study had been made of the nature and content of these nodules. Attempts were made to determine whether the quantity of nitrogen in the soil was increased by growing legumes. The early experiments of Lawes and Gilbert, as well as those of other investigators, were unsuccessful since, in the attempt to secure accurate data on nitrogen accumulation, the soil was ignited to drive off all traces of organic matter and thus all the soil bacteria were incidentally destroyed.

In 1886, Hellriegel and Wilfarth finally proved that the nitrogen of legumes may be secured from the air, provided the necessary nodule bacteria are present in the soil. Table 26 gives a portion of the data from one of their experiments in which lupines were grown in pots in nitrogen-free sand. Some of these pots were watered with distilled

TABLE 26

NITROGEN CONTENT OF LUPINES* GROWN IN NITROGEN-FREE SAND (WILFARTH)

Number of Pot	Treatment of Sand	Dry Weight† of Lupines	Nitrogen† in Lupines
3	Soil solution	44.73	1.009
4	" "	45.63	1.156
5	" "	44.68	1.194
6	" "	42.45	1.337
9	Distilled water	0.93	0.014
10	" "	0.80	0.013
11	" "	0.92	0.013
12	" "	1.02	0.013

* A legume that is widely used for green-manuring purposes on acid sandy soils in northern Germany.
† Grams.

water and the remaining ones with a solution secured by extracting with water a soil on which lupines had previously been grown successfully.

The only possible source of the nitrogen in the plants grown in these experiments, other than the small amount contained in the seed, was the air. There is now available a considerable amount of data showing that, in the absence of combined nitrogen in the soil, legumes are able to secure enough of this element from the soil air to satisfy all their requirements through the aid of the bacteria which live in the nodules on their roots. The soil requirements of the nodule bacteria are apparently quite similar to those of the legumes with which they are associated.

The symbiotic nitrogen-fixing bacteria belong to the genus *Rhizobium.* They are rod-shaped and do not produce spores. They often take on peculiar X, Y, T, and clublike forms. Those taken from the nodules of one species of legume may or may not produce nodules on another species of legume. To date, 21 cross-inoculating groups of rhizobia have been recognized, and 6 species have been given individual names. The bacteria within any one of these cross-inoculating groups will inoculate all the legumes in that group. Occasionally they will inoculate legumes which are outside their group, but the performance of the bacteria under such conditions is not satisfactory. The list of groups in Table 27 contains most of the legumes which are agriculturally important.

TABLE 27

Cross-inoculating Groups of Legumes

1. Alfalfa, sweet clover, and bur clover.
2. Red, crimson, white, alsike, and mammoth clovers.
3. Garden, field, and sweet peas, and vetch.
4. Garden, navy, and kidney beans.
5. Lupines, both the annuals and perennials.
6. Soybeans.
7. Locusts.
8. Cowpeas, lima beans, peanuts, lespedeza, and crotalaria.

The biological strains of any given species of *Rhizobium* vary enormously in their ability to fix nitrogen when in association with a given legume. One of the important tasks confronting the producers of inoculating cultures is that of selecting highly efficient strains of nodule bacteria and multiplying them for commercial purposes.

THE FIXATION OF NITROGEN BY NON-SYMBIOTIC BACTERIA

In addition to the nodule bacteria of legumes, commonly known under the genus name of *Rhizobium,* there are two other highly important groups of nitrogen-fixing bacteria which inhabit the soil. The latter are not associated with crop plants but function independently of them, in soils. The most important of these, which was discovered by Beyerinck in 1901, has been given the generic name of *Azotobacter*. Several species of the genus *Azotobacter* have been identified, the best known of these being *Azotobacter chroococcum*. These bacteria have been found to be rather generally distributed in soils. Under optimum conditions in the laboratory, it has been shown that as much as 200 pounds of nitrogen in 2 million pounds of soil may be accumulated by them from atmospheric sources in three weeks' time. Optimum conditions for the fixation of nitrogen involve the presence of adequate amounts of available carbohydrates, available phosphates, carbonate of lime, and moisture. A further requirement is an abundant supply of oxygen.

A group of non-symbiotic, nitrogen-fixing bacteria of the anaerobic type was discovered by Winogradsky, in 1893. These have been given the species name of *Clostridium pastorianum*. They seem to function effectively in soils that are acid in reaction, and under conditions that are unfavorable to most species of *Azotobacter*. It has been suggested that these two groups of bacteria may effect a symbiosis in which the *Clostridium* supplies a source of available carbon in the butyric acid which it produces, while the *Azotobacter* tends to develop anaerobic conditions as a result of its oxidation of organic materials.

Nitrogen fixation is probably a function of other species of soil bacteria under conditions in which the supply of soluble nitrogen is very limited. Probably the nodule bacteria of legumes fix some nitrogen while living in the soil during the periods between the legume crops in the rotation. In such quantitative tests as have been made of these processes, the conclusion has been reached that of the non-symbiotic groups the *Azotobacter* is perhaps the most efficient. It is probable that the legume bacteria, during the time in which they are growing in the nodules, are more efficient than any of the others. On the other hand, the non-symbiotic bacteria have the advantage in that they may be more or less continuously at work in the soil, assuming favorable conditions as to temperature, reaction, moisture, and food supply.

THE MINERALIZATION OF ORGANIC MATTER

In addition to carbon, hydrogen, oxygen, and nitrogen, the four elements that constitute the major portion of the organic matter in the soil, plant residues also contain the elements calcium, magnesium, potassium, sulfur, phosphorus, and other inorganic elements which are liberated for crop use in the process of decay. As the organic matter is decomposed, any excess of acid, above that required to form salts with the basic elements liberated, may have an opportunity to act on the previously undissolved soil minerals, with the consequent liberation of additional amounts of the several nutrient mineral elements. If all the nitrous acid formed in the decay of a 10-ton application of good manure came in contact with the mineral apatite in the soil, enough phosphorus would be dissolved to produce several 100-bushel crops of corn. Undoubtedly such acids will react for the most part with silicates and limestone. As a result, potassium, calcium, and magnesium, as well as some phosphorus, may be changed to soluble forms.

BIOLOGICAL ANALYSIS OF SOILS

In general, it may be said that the greater the number of bacteria in soils, the more productive the soils are likely to be. The counting of the number of bacteria in a gram of soil is a means of diagnosing the condition of the soil, but gives no explanation of its productivity or lack of productivity. This is true also of the data secured from studies of the rate of nitrate accumulation, nitrogen fixation, or carbon dioxide evolution, which may occur under standardized conditions in the laboratory.

If, however, the soil is in a low state of productivity, the efficacy of a suggested remedy may be fairly satisfactorily determined in the laboratory, in a few days or weeks, by measuring the effect of the treatment on nitrate accumulation, on carbon dioxide evolution, or on some other bacterial process which normally is more active when the productivity of the soil is increased. The effectiveness of liming the soil can be readily determined by studying the rate of accumulation of nitrates in the soil. Applications of limestone and phosphates may result in a marked increase in the nitrogen-fixing powers of *Azotobacter*. A biological analysis of a soil, therefore, provides a clue to its state of productivity and permits of determining in a relatively short period of time the probable efficacy of any treatment that one may contemplate using under field conditions.

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CHAPTER VII

SOME PHYSICAL PROPERTIES OF SOILS

The physical properties of soils are determined largely by the size and arrangement of the primary particles of which they are constituted. For this reason, it is desirable, in studying any given soil, to know the percentages of the different-sized particles contained in it and the manner in which these particles are arranged in the soil as it exists in the field. A sandy soil, for example, contains a high percentage of relatively large particles, as compared to those which make up a large portion of a clay soil. The surface area of the particles in a given volume of sandy soil is very much less than that of the particles in the same volume of a clay soil. As a result, a sandy soil has less capacity to retain water and to adsorb soluble salts that may be in solution in this water than has a clay soil. Sandy soils, therefore, are more subject to drought and to nutrient deficiencies than are clay soils. On the other hand, clay soils often take on a bad physical condition when, for any reason, the aggregates composing them are broken down into primary particles.

MECHANICAL ANALYSIS OF SOILS

The mechanical analysis of a soil has for its purpose the determination of the percentages of the various-sized primary particles of which it is constituted. Particles which have such small dimensions as to be termed clay tend to arrange themselves in groups, or aggregates, which must be broken apart before the analysis can be made. Various methods have been employed for effecting this purpose, of which shaking the soil in a dilute solution of ammonium hydroxide was one of the earliest. Present methods call for treating the soil with 0.2 normal hydrochloric acid, washing it to remove the displaced cations, and then shaking it for 10 hours in a 0.1 normal solution of sodium hydroxide. Preliminary boiling in a 6 per cent solution of hydrogen peroxide, to oxidize the organic matter, is necessary in soils high in humus.

After dispersion of the primary particles has been effected, the particles are then separated into sand, silt, and clay fractions, the weight of each being determined and recorded. The sand is separated from the finer particles by washing the sample on a fine-meshed sieve. The silt and clay which pass through the sieve are separated by sedimentation and decantation, use being made of a centrifuge. The water suspension of the clay is evaporated to dryness, and the resulting product weighed.

It is apparent that the above procedure is long and tedious. For that reason, attempts have been made to find a more convenient method of estimating the proportions of the various separates in the soil. Of the several procedures, that involving the use of a hydrometer is in common use. In this method, use is made of a specially constructed hydrometer which is placed in a sedimentation cylinder containing the soil in suspension. By making hydrometer readings at definite time intervals, one can determine the percentages of the various-sized particles in the sample of soil. The ease with which this can be done is such that most routine mechanical analyses of soils are now made by this method.

SOIL SEPARATES

The several sizes of primary soil particles are arranged into groups called *separates*. The dividing lines between the several separates, which are now generally employed, are as follows:

TABLE 28

Soil Separates Adopted by the International Society of Soil Scientists

Separate Names	Diameters* in Millimeters
Gravel	2.0 and larger
Coarse sand	2.0 to 0.2
Fine sand	0.2 to 0.02
Silt	0.02 to 0.002
Clay	0.002 and smaller

* The particles are not necessarily spheres. Diameters may be taken to mean their longest dimensions.

These divisions are made more or less arbitrarily. However, it has been pointed out that certain fairly definite differences in particle properties occur at the dividing lines which are now being employed. Thus, water begins to be held weakly in the pore spaces at 2.0 millimeters; capillary attraction operates most efficiently at 0.2 millimeter; particles tend toward crumb formation at 0.02 millimeter; and Brownian movement begins to be exhibited at 0.002 millimeter.

This classification was not adopted by the Bureau of Soils of the United States Department of Agriculture until 1937. Before that date, silt separates were confined to particles with diameters between

0.05 and 0.005 millimeter, and clay separates to particles with diameters that were less than 0.005 millimeter. In Illinois' surveys, the range in particle diameters was between 0.03 and 0.001 millimeter for silt, while clay comprised those particles whose diameters were less than 0.001 millimeter. Similarly, in the English system of nomenclature, silt particles ranged between 0.01 and 0.002 millimeter in diameter, and the clay separate contained all the remaining smaller particles.

SOIL CLASSES

The words sand, silt, and clay, when used as adjectives modifying soil, refer to soil *classes* whose predominating particle sizes are those indicated by the separate name employed. Thus, a clay soil, as formerly defined by the Bureau of Soils, was one that contained 30 or more per cent clay and at least 50 per cent silt and clay combined. It is now defined as one containing 50 or more per cent clay.

The soils of the United States are now grouped into 12 major classes according to the predominance of one or another of the separate groups of particle sizes, or on the basis of what is said to be their texture. The specifications for these classes are indicated somewhat in the class names, as shown in Table 29.

These classes are divided into three groups, according to their percentages of clay, namely: those containing less than 30 per cent clay, those containing 30 to 40 per cent clay, and those containing 40 or more per cent clay.

TABLE 29

Some Important Soil Classes of the United States (Kellogg)*

Soil Classes	Sand, Per Cent	Silt, Per Cent	Clay, Per Cent
Loam	20–50	20–50	30 or less
Silt loam	20 or less	50–100	30 or less
Sandy clay loam	40–70	0–20	30–40
Clay loam	20–50	20–40	30–40
Silty clay loam	0–30	40–70	30–40
Sandy clay	30 or more	......	40–50
Silty clay	......	30 or more	40–50
Clay	......	......	50 or more

* Tentatively proposed for soils of medium and heavy textures.

THE COLLOIDAL MATTER IN SOILS

Of particular interest from the physical point of view is the quantity and nature of the colloidal matter in soils. Since clay is defined as a soil separate, the particles of which have diameters of .002 millimeter or less, the question naturally arises as to the lower limits of these particle sizes. Evidently, the lower limit of particle size will be that of the molecule at which point solution occurs. A molecule of hydrogen is estimated to have a diameter of 0.16 by 10^{-6} millimeter, and a molecule of chloroform, a diameter about eight times that length. The longest dimension of a molecule of kaolin would undoubtedly be somewhat greater. However, between the longest dimension of an aggregate of molecules of kaolin and that of the largest particle of clay is a very wide range of dimensions. As the state of division of a given mass of soil becomes finer, the total surface area of its constituent particles also increases, although not in the same proportion. The relation between particle size and surface area is shown in Table 30.

It will be observed that with each reduction of particle size to one-tenth the previous size, the number of particles is increased one thousand times. At the same time, their total surface area is enlarged ten times. It is the area enlargement which is of most significance. If all the particles contained in an acre of soil to plow depth had diameters of 1 millimeter each, the total internal surface area in the acre would be less than 500 acres, as compared with 5,000,000 acres if the particle diameters were only 0.0001 millimeter. In the latter case, the forces of cohesion and adhesion would become very apparent in their effects. The particles of soil would have a tendency to stick together, and the soil water and the substances dissolved in it would tend to adhere to the surfaces of these particles.

TABLE 30

NUMBERS AND SURFACE AREA OF PARTICLES* IN A GRAM OF SOIL

Diameter, Millimeters	Particles, Number	Surface Area, Square Millimeters
1.00000	72×10	226×10
0.10000	72×10^4	226×10^2
0.01000	72×10^7	226×10^3
0.00100	72×10^{10}	226×10^4
0.00010	72×10^{13}	226×10^5
0.00001	72×10^{16}	226×10^6

* Assuming spheres of given diameters with specific gravity 2.65.

It is apparent that soils containing high percentages of material in the colloidal state are likely to offer serious competition against the plant for water and for mineral nutrients in the soil solution. Similarly, the rate of movement of water through such soils may be very much reduced, and the losses of compounds through leaching may be very much lessened. Difficulties may be encountered in plowing the soil, in preparing it for crops, and in securing effective drainage. However, much depends upon the arrangement of these particles in the soil because they may exist either in a deflocculated or in a flocculated state.

ESTIMATING THE COLLOIDAL CONTENT OF SOILS

The previous discussion of the soil separates and their particle dimensions would indicate that there is a range of particle sizes from those that are classified as sand to those that approach the molecular state. The mechanical analysis of a soil is made on that assumption. Investigation shows not only that most clay particles are merely aggregates of much smaller particles of colloidal dimensions but also that many of the silt particles are similarly constituted. From a study of thirty-two samples of soil investigated by Gile and his associates, the conclusion was reached that the colloidal content ranged from 6 to 61 per cent, all particles whose diameters were 1 micron or less being included under the term colloidal. In many samples the percentage of colloidal material exceeded that of the clay separate as determined by the usual method of mechanical analysis.

It is evident that if the soil contains such high percentages of colloidal material, this material is not only present as a thin gelatinous film around the coarser particles but also occupies a considerable portion of the space between these larger particles. Depending upon its nature, this colloidal material must play an important part in determining not only the physical characteristics of the soil but the chemical characteristics as well. In fact, it is by taking advantage of the peculiar properties which finely divided matter may possess, that it is found possible to estimate the colloidal content of the soil without going through the very laborious process of separating this material from the soil mass. The method employed in this determination is that of measuring the soil's capacity to absorb some suitable substance, such as ammonia, malachite green, or even water itself. This is, in effect, a rough measure of the surface area of the soil colloids, although it must be admitted that the chemical nature of the colloidal matter probably is an important factor in determining its capacity to absorb materials from solution.

THE STRUCTURE OF SOILS

In the above discussion, it has been largely assumed that the particles of soil are spheres. This is not so. Examination under the microscope reveals that the larger particles are covered with masses of more or less translucent material of a gelatinous nature. When this has been removed with hydrogen sulfide and dilute oxalic acid, the enclosed particle is found to be an angular fragment of mineral, the nature of whose surface depends upon the mineral which comprises it. The colloidal material surrounding these particles may be either organic or inorganic in its nature but is usually made up largely of the inorganic type of material.

It is a well-known fact that colloidal particles, such as exist in the clay separates of soils, may exist either in a highly peptized state or in granulated masses, depending largely upon the relative amounts of the several cations in the exchange complex. It is also a matter of common experience that working clay soils when they are wet tends to compact them. This is explained on the basis of the destruction of the granular *structure* in which their colloidal particles had arranged themselves as a result of the action of certain forces which had previously operated.

The condition of a clay soil in its granulated and its dispersed states may perhaps be safely compared with that of bread in its loaf and dough stages, respectively. If either the bread or the clay soil is rolled between the thumb and the finger when it contains a certain excess of moisture, a doughy mass results. With clay, freezing and thawing, and drying and wetting are useful in bringing it back to its granulated state. The dispersion which occurs in wet and acid soils can usually be overcome by draining and liming. Such alkaline compounds as the hydroxides and carbonates of sodium and potassium have peptizing effects, as is well known in regions of alkali soils.

Some soils do not possess a definite structure since the several particles function individually. This holds true with soils that contain little or no material of colloidal dimensions. The most difficult problem in this connection is presented in soils that are made up largely of very fine silt, the particles of which fit together very compactly. If such material is cemented together by iron oxides or humates, it forms a hardpan layer which may be almost impervious to water. Impervious layers are also formed in acid soils, in which the highly peptized colloidal matter gradually finds its way to lower levels where it tends to accumulate and form tight layers of subsoil.

THE NATURE OF CLODS

Clods may be classified into three main varieties. The most common are those which result from working finely textured soils when they are wet. Under such conditions the crumb structure is destroyed, and the particles become so closely associated with each other in much enlarged masses that the usual lines of weakness no longer exist and the cohesive forces have opportunity to be effective. A second variety of clods results from plowing a soil while it is too dry. Such clods are of the

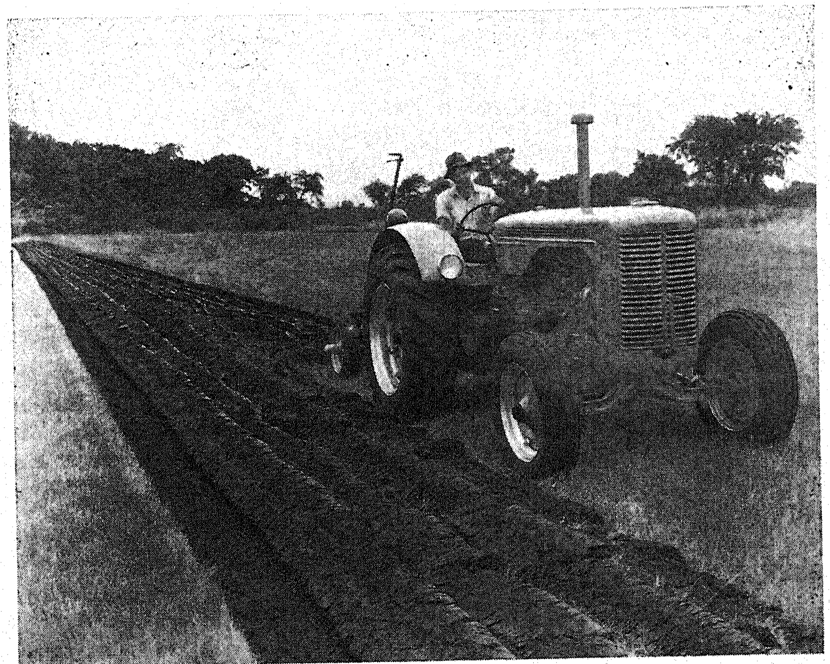

FIG. 11. Nothing quite takes the place of a good sod as a granulating and tilth-improving agent for soils.

nature of overgrown granules which readily break apart when the soil becomes moist. A third type of clod may be formed in soils that are largely composed of the finer particles of silt which have been compacted through the action of rain and which tend to break up in the form of clods. Clay soils also tend to "run together" as a result of the continued action of rain which, if it falls with violence, has much the same effect as though the soils had been plowed wet. It is apparent, from the above considerations, that one of the most important factors involved in determining whether or not the soil will be in good tilth is the amount of water which it contains when it is being worked.

THE EFFECT OF ORGANIC MATTER

The marked effect of the presence of plant residues in soils on their working qualities is well known. The application of liberal amounts of manure and the incorporation of plant residues, including the roots, apparently have the effect of developing lines of weakness which prevent the forces of cohesion from being sufficiently effective to permit of the formation of clods. Repeated heavy applications of manure may so affect the physical characteristics of a clay soil as to make it take on the qualities of a loam. Occasionally, quite the opposite effect is noted. In soils that are somewhat wet and in which the oxidation of the added organic matter is relatively slow, the application of manure delays the drying-out process, with the result that in the early spring it may be difficult to find a favorable moisture condition at which to work the soil.

After these organic materials have undergone decomposition to the point at which they may be classed as humus, they constitute an important portion of the colloidal matter of soils. In sandy soils this is of particular importance in that the humus serves in the same capacity as clay to form a binding material for the coarse particles. In clay soils, the colloidal humus tends to bind the finely divided particles together in the form of granules. During periods of drought, these organic colloids are dehydrated, and rehydration is very slow. Their granulating effect is more permanent than is that produced by inorganic colloids.

Under favorable conditions of drainage, reaction, and moisture supply, soils belonging to the various classes may have their original characteristics so masked by incorporating large amounts of organic materials with them that the differences in their physical qualities are largely obliterated.

VARIATIONS IN SOIL PROFILES

The nature of the subsoil is as important as that of the surface soil in determining the crop-producing capacity. While the characteristics of the surface soil more or less reflect the condition of the subsoil, they do not always provide a reliable clue to the remedy that may be required to improve the physical properties of an unproductive soil. It is particularly important to know whether or not any of the horizons of the subsoil are only slowly permeable to water. If they are, it is desirable to determine the exact location of these horizons and the nature of the soil material in them in order to know how to proceed to overcome this condition. Lines of tile may be so placed in the subsoil as to be ineffective, if the location of these impervious layers is not taken into consideration.

The profiles in Table 31, representing four important soil types, show the variations in physical properties of the horizons down to the rock material. From a study of these profiles, one can anticipate the suitability of these soil types for growing a given crop and also estimate the probable usefulness of any contemplated scheme for improving their physical characteristics.

TABLE 31

PROFILES OF FOUR IMPORTANT SOIL TYPES

I. *Podsol* — northern, gray, timbered soil — Minnesota.	
0–3 in.	Leaf litter and mold, dark brown in color, mostly disintegrated, but very little decomposition, largely derived from mixed conifer and deciduous tree leaves.
3–4 in.	Dark gray silt loam.
4–9 in.	Very light gray silt loam with single-grain structure or with a very slight development of the platy structure.
9–17 in.	Very dark grayish-brown, heavy silty clay, plastic when moist, hard and breaking into angular fragments when dry.
17–40 in.	Gray, very calcareous, heavy-textured glacial drift.
II. *Miami loam* — brown, timbered soil — southern Michigan.	
0–1 in.	Leaf litter and mold from deciduous trees, decomposed at base, grading into mineral soil below.
1–4 in.	Grayish-brown loam, the organic matter content gradually decreasing with depth; reaction generally neutral.
4–12 in.	Light yellowish-brown loam with a decided grayish cast when dry, acid in reaction.
12–27 in.	Yellowish-brown heavy clay loam, rather sticky when wet, hard but readily breaking into angular fragments when dry.
27–40 in.	Heavy-textured, calcareous glacial drift.
III. *Marshall silt loam* — humid prairie soil — Iowa.	
0–11 in.	Dark grayish-brown silt loam; loose silty structure.
11–18 in.	Dark grayish-brown color, changing downward to brown; more compact than surface soil; very granular.
18–27 in.	Yellowish-brown or brown, compact, heavy silt loam; granular.
27–36 in.	Yellowish-brown, heavy silt loam; slightly lighter in color and less compact than the 18- to 27-inch horizon; granules gradually become less perfect.
36–48 in.	Soft, structureless, over light material; somewhat variegated or spotted in color, but this mottling is not due to poor drainage.
IV. *Norfolk fine sandy loam* — yellow, timbered soil — Carolinas.	
0–3 in.	Gray, loamy, fine sand with a slight mingling of organic matter.
3–16 in.	Grayish-yellow, loamy, fine sand; single-grain structure.
16–48 in.	Yellow, fine, sandy clay, friable and crumbly.
48–96 in.	Mottled light red, reddish-yellow, and light gray, brittle but friable material, showing some streaking with red and yellow; soft iron concretions are present.
96–120 in.	Mottled gray and yellow material.

RELATION OF TEXTURAL TO CHEMICAL COMPOSITION OF SOILS

The soils of humid regions tend to become somewhat stratified as to sizes of particles, the coarser ones remaining on the surface and the finer particles gradually concentrating in the lower horizons. This tends also to effect a stratification of the nutrient constituents for the reason that the coarser-textured particles are more largely quartz whereas the finer particles are colloidal silicates which absorb and hold the plant nutrients. If the soil is composed of transported materials, a different type of stratification may occur, in which very little regularity is to be expected as between different soils. In arid regions, where weathering is more disintegration than decomposition, the various-sized particles may differ very little in chemical composition.

In general, it may be said that the coarser separates of the soils of humid climates contain higher percentages of silica, while the finer separates are relatively more concentrated in iron, aluminum, phosphorus, calcium, magnesium, sodium, and potassium. Except for iron and aluminum, the higher percentages of these elements in the finer separates may be explained as due, in part, to the effectiveness of the

TABLE 32

PERCENTAGE COMPOSITION OF SOILS AND THEIR COLLOIDS (ROBINSON)

Oxides	Cecil Clay Loam		Marshall Silt Loam		Norfolk Fine Sandy Loam	
	Soil	Colloid	Soil	Colloid	Soil	Colloid
SiO_2	83.81	33.95	72.06	45.93	90.34	38.25
TiO_2	0.80	0.62	0.67	0.48	0.94	0.79
Al_2O_3	7.70	36.06	11.18	21.72	2.89	31.21
Fe_2O_3	2.97	11.02	3.66	8.94	1.88	11.25
MnO	0.20	0.15	0.05	0.07	0.00	0.03
CaO	0.28	0.31	0.90	1.19	0.01	0.54
MgO	0.15	0.40	0.66	2.01	0.08	0.53
K_2O	0.79	0.56	2.66	2.28	0.22	0.26
Na_2O	0.43	0.44	1.02	0.21	0.04	0.09
P_2O_5	0.06	0.25	0.21	0.46	0.02	0.23
SO_3	0.02	0.06	0.12	0.21	0.03	0.08
Cl	0.02	0.04	0.05	0.06	0.04	0.05
H_2O*	....	14.42	....	7.92	....	11.92
N	0.03	0.22	0.23	0.51	0.06	0.22
Colloid†	10.20	....	27.30	....	10.70	....

* Combined water.

† Per cent of colloid in soil as estimated by absorption method.

surface forces of the soil particles in retaining ions which would be readily leached out of coarse-textured particles.

Although soils usually contain large percentages of silica, nevertheless considerable amounts of it are leached out in humid climates.

The high content of silica in the surface soil and in the coarser separates indicates a large percentage of quartz in the parent rock, with its well-known resistance to weathering agencies. Thus Table 32 is of interest in showing the percentage composition of soils in comparison with those of their colloidal fractions.

PHYSICAL ANALYSIS OF SOILS

The size and arrangement of soil particles has much to do with the water-and-air relationships in soils. They, therefore, affect fundamentally the biological properties of soil. As the colloidal content of the soil increases, its capacity to yield up nutrients to plants is affected, as well as its ability to retain any fertilizer elements that may be supplied. It is a well-known fact that the chemical analysis of a soil may show large amounts of the mineral constituents and yet the soil may be unproductive if for any reason the arrangement of its particles prevents the adequate circulation of water and air. The texture of a soil, in reference to its percentage contents of the various separates, can be determined by mechanical analysis. The effective structure, or the arrangement of these particles in a soil, is best determined by measurements of those properties which are expressions of the arrangement of its constituent particles. Physical analysis has to do with the determination of certain of these properties, such as water-holding capacity, pore space, permeability to water and air, plasticity, and cohesion. Unfortunately, laboratory studies of these physical properties are difficult to interpret in terms of field conditions since, in moving the soil to the laboratory, the natural arrangement of its particles is disturbed.

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CHAPTER VIII

THE WATER IN SOILS

The water-holding capacity of a soil is determined to a large degree by its texture and the nature and arrangement of its constituent particles. Ordinarily, it amounts to 30 to 50 per cent of the total volume occupied by the saturated soil in place. An acre of soil to a depth of 5 feet, a depth to which the roots of many crop plants often penetrate, might have a capacity for sufficient water to meet the requirements of two 50-bushel crops of wheat or an equal number of 100-bushel crops of corn, if none of this water were lost by drainage or evaporation, and all of that contained in the soil could be extracted by the plant roots. Evidence of this fact is found in the following table, which gives the percentage, by volume, of water required to saturate a 6-inch column of undisturbed soil to a depth of 5 feet.

TABLE 33

WATER REQUIRED TO SATURATE A 6-INCH COLUMN* OF SOIL (KING)

Depth, Feet	Character of Soil	Weight, Pounds	Water Required for Saturation		
			Pounds	Inches	Per cent†
0–1	Marly loam	15.09	6.24	5.88	49
1–2	Reddish clay	18.94	5.33	5.03	42
2–3	Reddish clay	18.89	5.38	5.07	42
3–4	Clay with sand	19.94	4.95	4.67	39
4–5	Very fine sand	22.92	3.99	3.76	31
Totals to depth of 5 feet		95.78	25.89	24.41	41

* A column 6 inches in diameter. † Per cent of total volume of soil.

THE CAPILLARY CAPACITIES OF SOILS

The water content of a saturated soil is considerably reduced by the action of gravity, if the conditions in the subsoil permit the withdrawal of the gravitational water. It happens also that soils are not in condition for the satisfactory growth of most crop plants until the gravitational water has been largely or entirely removed. Of greater interest, therefore, is the water-retaining power of a soil against the pull of gravity, or what is usually termed its capillary capacity. This is largely determined by the texture and structure of the soil, the temperature, and the height above the water table that is under consideration. The element of time is also of considerable importance, since often the gravitational water has not all reached the level of the water table before another rain occurs.

In an experiment, the data for which are recorded below, columns of soil were saturated with water, after which free percolation was allowed to take place for a period of sixty days. There was no standing water table at the base of these soil columns except as the water from higher levels tended to maintain the lower part of the column at the point of saturation throughout the period of the test. Evaporation was reduced to a minimum. The percentages given are those of the water that was present in 3-inch layers of soil chosen at 1-foot intervals to a height of 7 feet.

TABLE 34

WATER RETAINED BY SOILS AFTER 60 DAYS OF PERCOLATION (KING)

Height of Column, Inches	Per Cent of Water Retained*	
	Sandy loam	Clay loam
84	16.16	21.26
72	16.55	31.05
60	17.59	31.21
48	18.70	31.99
36	20.90	32.45
24	21.46	34.40
12	22.68	35.97
6	27.69	37.19

* Percentage of total volume of soil.

THE WILTING POINT OF PLANTS

It would seem from laboratory data that, if a field soil were saturated with water at the end of the spring rains, there would be an adequate supply of water for crop use after the normal loss of gravitational water had taken place, even though no rainfall occurred during the summer months. The water-retaining capacity of the top 3 feet of an acre of the sandy-loam soil amounts to over 7 acre-inches, while that of the same depth of the clay-loam soil is more than 12 acre-inches. However, there are two agencies that compete with plants for water; one of these is the soil itself, and the other is the atmosphere.

It is a well-known fact that plants wilt long before the soil is as dry as it would be if it had been subjected to artificial heat in a drying oven, or even if it had been simply air-dried. This is because the rate of loss of water by transpiration may become more rapid than its rate of capillary movement through the soil from points of higher moisture content to those at which it is being removed by the root hairs. *Wilting coefficient* is a term that has been coined to indicate the percentage of water in a soil at the time at which the rate of transpiration exceeds that of the renewal of the water by capillary means. At this point, wilting of the plant occurs. The following table shows the water content of various classes of soils at the wilting point of plants when grown in a saturated atmosphere. The *hygroscopic coefficient,* which is the percentage content of water in the soil when in equilibrium with a saturated atmosphere, is also shown.

TABLE 35

WILTING AND HYGROSCOPIC COEFFICIENTS* OF SOILS (BRIGGS)

Soil Class	Wilting	Hygroscopic
Coarse sand	0.9	0.5
Fine sand	3.0	1.9
Sandy loam	5.6	4.0
Fine sandy loam	9.7	6.5
Loam	12.1	8.8
Clay loam	16.3	11.4

* Percentages of water calculated on dry weights of soil.

To recalculate Briggs' percentages to a volume basis requires the use of a factor lying between 1.25 and 1.75, depending upon the texture of the soil, the factor for clays being the least. Using the first factor, it is found that 20.4 per cent, by volume, of King's clay-loam soil would have been occupied by water at the wilting point. Thus, the available water in the upper 3 feet of the clay-loam soil mentioned in Table 34 may be only about one-third of its retentive capacity, or 4 acre-inches. Furthermore, a considerable portion of this available water may be lost by evaporation from the surface of the soil during the period of growth of the crop plants. Experience has shown that, even though the soil and subsoil may have contained their full capillary capacities early in the season, dry periods at some later date are quite likely to cause injury from drought.

THE WATER-MAINTAINING CAPACITIES OF SOILS

An important physical property of soils in relation to crop production and distribution is their water-maintaining capacity. Under any given climatic environment, some soils tend to maintain a relatively high moisture content as compared with other soils. This tendency is related to their texture, their content of organic matter, the nature of their subsoils, and the location of the temporary or permanent water table. That this water-maintaining capacity of soils is often the determining factor in crop distribution is indicated by the fact that bluegrass pastures grow most luxuriantly under conditions of relatively high moisture content of soil, and tend to be replaced by weeds and poverty grass (*Danthonia spicata*) when the virgin humus supply has been dissipated. This explains the better growth of grass on the north than on the south exposure of a hill. It is commonly believed that chestnut trees grow only on non-calcareous sandy soils, but it has been shown that they grow equally well on the calcareous soils that overlie the Mammoth Cave of Kentucky. The important factor is the moisture relationship rather than the soil reaction.

The explanation of the fact that some soils are better adapted to cereal crops and others to potatoes, truck crops, or grass may be found in this same moisture factor. A suggestive classification of crops according to their requirements as to the water-maintaining capacities of the soil on which they are grown is given in Table 36. In this study, samples of soil were selected to a depth of 1 foot each day during the growing season, from fields in which crops, known to be adapted to the soil and climatic conditions, were being grown.

TABLE 36

CROP ADAPTATIONS AND WATER-MAINTAINING CAPACITIES OF SOILS (WHITNEY)

Crop Adapted to Soil	Location, State	Water Maintained*
Truck crops	Maryland	6
Wheat	Maryland	13
Grass	Maryland	18
Light tobacco	Connecticut	7
Dark tobacco	Pennsylvania	18

* Percentage of dry weight of soil.

RATE OF MOVEMENT OF AVAILABLE WATER

The amount of water available to plants is determined not only by the capillary capacity of a soil and the extent to which evaporation is under control, but also by the rate at which this retained water moves toward the points at which water is being removed as the result of losses through transpiration. The most satisfactory capillary movement of water is found in medium-textured soils of the loam and silt-loam classes. The total height to which water will rise above the water table is also greatest for these classes of soils. The most rapid rise over a short distance is found in coarse-textured soils, but the height to which the water will move in such soils is very much reduced. Both clay and sandy soils may be classed as dry soils except under conditions of adequate rainfall or in situations in which their surfaces are not too far removed from the water table. The following table is of particular interest in that it shows both the rate of flow and the total rise of capillary water in three different classes of soils. The soils were placed in cylinders, uniformly compacted, and the bottoms of the cylinders were then placed in vessels of water that was maintained at a constant level.

TABLE 37

EFFECT OF TEXTURE ON RATE AND HEIGHT OF CAPILLARY RISE OF WATER*

Time	Height of Water in Inches at Periods Indicated		
	Sand	Silt loam	Clay
½ hour	13.5	7.3	5.4
1 hour	14.3	11.2	8.0
6 hours	16.6	26.6	15.5
12 hours	17.2	35.3	18.5
1 day	18.4	46.4	21.0
3 days	20.3	65.4	24.7
6 days	21.8	78.5	27.3
9 days	23.0	86.3	28.8
18 days	25.3	99.2	33.2

* Air-dried soils were used in these tests.

In the above test, the soil was in the air-dry state and, as a result, the rate of flow was very much retarded. The effectiveness of the surface mulch in preventing the loss of water by evaporation is evidence of this fact. It has frequently been observed that a light rain may be of less value than none at all, since it moistens the surface layer of soil, makes contact with the moist soil beneath, and increases the rate of movement of water toward the surface, where it may be lost by evaporation. This principle is of considerable importance in connection with overhead irrigation, in which the policy of an occasional thorough wetting is much to be preferred to that of frequent light applications of water.

The rate of capillary movement of water is also increased by compacting the soil. It is because of this that the planter wheels are set to run over the newly planted seed. The use of a roller is effective in dry weather, as a means of hastening the germination of seeds. The footprints of someone who has walked across a newly seeded lawn are often very apparent in the more rapid germination and better growth of grass in these spots than on the remainder of the lawn.

THE SURFACE MULCH

The rate of loss of water by evaporation from soils may be very materially reduced if their surfaces are thoroughly dried. This occurs naturally if sufficient time elapses between rains. However, it is the time factor that is important. In semi-arid climates, the rate of drying of the surface soil is so rapid that no supplemental treatment of the soil to hasten the process seems to be necessary. In humid climates, this may not hold true. In that event, it may be desirable to cultivate the

FIG. 12. Organic materials make the most effective mulches. They absorb all the rainfall and prevent its loss by evaporation.

soil as soon as possible after each heavy rain in order to produce a dry surface layer before serious losses from lower depths have occurred.

The efficiency of the surface mulch in preventing the loss of water from soils is indicated in the following table. In this test the columns of soil, having depths of about 12 inches, were contained in evaporimeters, at the bottoms of which water was added as fast as it was lost by surface evaporation. Mulches were maintained to depths of 1, 2, 3, and 4 inches, respectively, by stirring the soil from time to time in almost the same manner as it would have been done by the ordinary cultivator in field practice.

TABLE 38

TONS OF WATER EVAPORATED FROM ACRE OF SOIL WITH AND WITHOUT MULCH* (KING)

Depth of Mulch	Clay Loam	Black Marsh	Sandy Loam
None	2414	588	741
1 inch	1260	355	373
2 inches	979	270	339
3 inches	889	256	287
4 inches	883	252	315

* Data for a period of 100 days.

Under the conditions of the above test, the losses of water by surface evaporation were practically cut in half by the use of a mulch. There has been considerable discussion of the above and similar data in recent years by reason of the discrepancies that seem to exist between the results obtained by laboratory means and those secured under certain field conditions. The failure to take into consideration the crop, the climate, the season, and the soil, as factors which determine whether or not moisture will be conserved by surface cultivation, is responsible for much of the confusion that exists on this subject.

Data secured by measuring crop yields, or by determining the moisture content of soils on which crops are being grown with and without cultivation, cannot safely be used to determine whether or not cultivation conserves water. The elimination of such data simplifies the consideration of the fundamental principles that are involved. The following statement of Cameron, published in 1907, outlines the matter as well as any that has been made on this subject.

> Mulching decreases or inhibits the capillary flow, and diffusion through the mulch is practically negligible. This practice is very effective in conserving soil moisture and is founded on sound scientific principles. An especially interesting illustration is brought out in the comparison of the loss of water from a soil under arid and humid conditions, respectively. As might be expected, the loss at first is much more rapid under arid conditions, so rapid in fact as to tax the soil's ability to move water from within to the surface by capillarity, and in consequence a dry layer is formed which keeps the subsequent losses far below those which take place from the soil under humid conditions, where the capillary flow to the surface persists until the moisture content of the whole soil is very low indeed. These laboratory experiments, therefore, clear up in a very satisfactory manner the apparently contradictory facts, observed in the field, that the

soils of arid regions, at depths a little below the surface, are generally wetter and hold their moisture for much longer periods than do the soils of humid areas in dry seasons.

This explains the reason why data secured in areas in which the rate of evaporation of water is very rapid, by reason of dry winds of relatively high velocities, do not show any appreciable conservation of water by the use of the surface mulch. It serves as an explanation of the following experimental results, which were secured at Manhattan, Kansas.

TABLE 39

GAIN OR LOSS* IN SOIL WATER AS RESULT OF SURFACE MULCH (CALL)

Year	Rainfall†	3-inch Mulch	6-inch Mulch	Bare Surface
1914	17.93	−3.31	−1.86	−0.89
1915	44.97	0.70	−0.05	−0.70
1916	29.89	−2.39	−1.19	−2.50
1916 (diked)	29.89	0.20	2.37	2.88

* Gain or loss, expressed as per cent of water in the soil to a depth of 6 feet, in the autumn as compared with that in the spring.

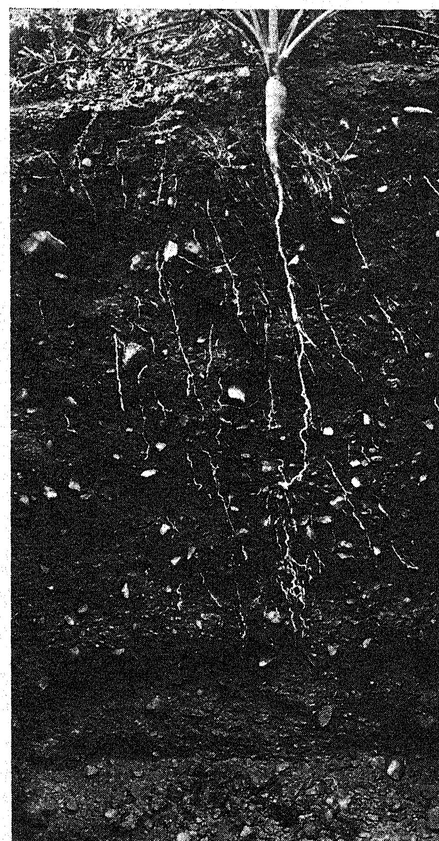
† Rainfall from January to September. The rainfalls for 1915 and 1916 were considerably above the average for that region.

It should be noted that in 1916 a portion of the field was diked to prevent surface run-off and, as a result, the soil contained more water than where it was not diked. This indicates a possible benefit from cultivation, other than that of preventing evaporation of water. On the whole, the data indicate that the ordinary surface mulch is of no great benefit in preventing evaporation of water from the soil in the Great Plains area. This is what is to be expected from the nature of the climatic conditions which obtain in that region.

DEPTH OF PENETRATION OF PLANT ROOTS

The need for large amounts of available water in the soil a few inches below the surface becomes less as the roots of the growing crop penetrate the subsoil. Light rains become less and less effective and surface mulches of less importance, since the available water is now that which lies at lower levels and has little chance to escape beyond the reach of widely spread systems of roots bearing very large numbers of root hairs. It is probably because of this that cultivation tests with corn in humid climates have not yielded as good results as would have been expected from consideration of the effect of the surface mulch.

Studies of the root systems of crop plants have shown that many of them extend to depths of 3 or more feet if the conditions in the subsoil are favorable for their development. In soils with an adequate nutrient supply, the most important factor in determining the depth to which the roots will extend is the moisture content of the soil. In general, it may be said that a relatively low content of moisture in the surface soil favors a well-developed root system. This is particularly important in the early period of growth of the crop; a moderately dry season for starting the crop is much preferred to a wet one.



H. C. Thompson, Cornell Agr. Exp. Sta.

FIG. 13. The root system of a half-grown carrot, in Dunkirk gravelly sandy loam soil.

Some idea of the relation between top and root growth of crop plants may be secured from the following table, which shows the depth to which the roots had penetrated the soil in certain areas in Nebraska, Kansas, and Colorado where no interfering factors in the subsoil prevented their development.

TABLE 40

ROOT DEVELOPMENT OF CROP PLANTS (WEAVER)

Variety of Crop	Growth of Tops		Growth of Roots	
	Age, days	Height, feet	Depth, feet	Spread, feet
Oats — Swedish Select	63	3.0	6.8	1.3
Wheat — Marquis	93	2.7	6.7	1.3
Barley — Manchuria	84	2.3	6.3	1.3
Corn — Silver Mine	116	8.5	8.2	4.0
Potatoes — Early Ohio	94	2.3	4.7	2.1

Some plants have relatively shallow root systems. If such plants are not xerophytic in their nature, they flourish only under conditions of frequent and abundant rainfall, where the climate is cool and moist, or where the water table is maintained relatively close to the surface by continued movement of water from surrounding higher levels. In irrigated sections, advantage is taken of these differences in the root systems of plants to kill the weeds in old alfalfa. (Alfalfa is the last to suffer from enforced drought.) Land difficult to drain and which is continuously wet is quite commonly given over to shallow-rooted pasture grasses or to such crops as cranberries.

LATERAL MOVEMENT OF WATER IN SOILS

While there would seem to be nothing to prevent the lateral capillary movement of water in soils, it does not seem to take place to any considerable extent. This is probably because the forces of gravity, transpiration, and evaporation operate to move the water vertically. The differences in water content of areas of soil lying in the same horizontal plane are not likely to be very marked. Of considerable interest in this connection is the lack of lateral movement of fertilizer salts. This is very well shown in the permanent grass plots at the Rothamsted Experiment Station, where differences in the growth of the grass and in the nature of the weeds are very sharply defined at the otherwise unmarked lines separating the several plots on which the fertilizers have been applied, although the experiment has been in progress for nearly a century. This points to the desirability of thorough lateral distribution of such materials as limestone, which need to be brought into contact with every portion of the soil. The lateral diffusion of the dissolved material is too slow to be depended on.

OPTIMUM WATER CONTENT OF SOILS

Considered from the point of view of its relation to plant growth and to the activities of the microbiological population of the soil, the optimum water content seems to be about two-thirds the amount required for saturation. It is apparent that plants and soil bacteria are not working at their highest efficiency for any considerable portion of their time under ordinary climatic conditions, since the moisture content of the soil varies between wide extremes during the growing season. Conditions of drought tend to hasten maturity of most crops, while abundant moisture has much the same effect in stimulating vegetative growth as do applications of nitrogenous fertilizers. This introduces an interesting point in connection with the practice of using fertilizers. It is possible to offset either the tendency to mature or to produce excessive vegetative growth by selecting fertilizers that produce the opposite effects.

The working qualities of most soils are also at their best at about two-thirds saturation. However, a notable exception to this is found in sand which, for best results, is worked in a condition that might be considered a little overwet. The practical difficulty is found in meeting the requirements of the various classes of soils that are often present in the same field. Furthermore, cultural operations cannot ordinarily be completed in a short enough time to take advantage of the most suitable amount of water throughout the entire period required.

OTHER MOISTURE RELATIONSHIPS

There is no sharp line of demarcation between hygroscopic and capillary water, nor between capillary and gravitational water. For that reason it seems advisable to study the water relationships of soils under certain standard conditions. Of such studies, those dealing with what are called the hygroscopic coefficients, the wilting coefficients, and the *moisture equivalents* of soils are of particular interest. The first two have previously been considered. The last may be defined as the amount of water that is retained by a soil when a layer 10 millimeters in depth is placed in a centrifuge and subjected to a force of 1000 times gravity for a period of forty minutes. Such a procedure gives comparative data as to the effective textural and structural conditions of soils.

Of the more recent techniques which have been developed for studying the moisture relationships in soils, that involving the use of a *tensiometer* has most interesting possibilities. This instrument consists of a porous cup which is sealed onto a manometer tube. The cup and part of the manometer are filled with water through a side opening which is then corked and sealed. This water is in direct contact with the mercury column, the height of which fluctuates with the tension between the water in the porous cup and that in the soil. This instrument is useful only as long as the tension does not exceed 1 atmosphere. However, this allows for knowing when the soil-moisture supply has fallen to a point where the lack of water is beginning to be a limiting factor in plant growth. Where artificial watering can be resorted to, the tensiometer provides a means of knowing when more water should be supplied. It can also be used to record the moisture conditions that obtain under different systems of soil management as, for example, under clean cultivation, organic mulch, and sod systems in orchards.

SOIL MANAGEMENT IN RELATION TO WATER CONTROL

As previously indicated, the available water supply in soils is of primary importance in determining the yield of crops. Those farming practices that are concerned with the control of the water content in such a manner as to prevent its being a limiting factor, either by reason of an excess or a deficiency, are of primary importance in successful soil management. Tillage operations, drainage, the various types of irrigation, and those practices that have to do with increasing the quantity of organic matter in the soil merit especial attention in this connection. Soils that are in a low state of productivity often produce very satisfactory yields in seasons of favorable moisture conditions even though no extra effort has been put on them. This would indicate that more attention might perhaps be profitably paid to those farming operations taken up with water control. On a well-managed farm, it is seldom necessary for the crop to suffer serious injury either from drought or from standing water.

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CHAPTER IX

THE AIR IN SOILS

The giving off of carbon dioxide is a function both of the leaves and of the roots of crop plants. It is necessary, therefore, that ventilation processes be in operation to effect a change in the air at all points of its contact with plants, in order to prevent the accumulation of this respiratory product. For the leaves of plants, this is accomplished through the action of winds and air currents. In the soil, the processes of ventilation are more complicated. Special attention must often be given to this problem in order that the air in contact with the roots of plants may be more frequently renewed.

PORE SPACE IN SOILS

The pore spaces in soils, as previously indicated, amounts to 30 to 50 per cent of the total volume. Part of this space is taken up by water, and the remainder by air. As the quantity of water is increased, the rate of diffusion of the constituent gases of the air between the atmosphere and the soil is very much reduced. A point is finally reached at which most crop plants begin to show signs of injury. If the soil is saturated with standing water for any considerable length of time, the death of such plants occurs. While death results, in such cases, from the lack of ventilation of the soil, the immediate cause of the trouble is not so readily determined. It may be due to the accumulation of carbon dioxide, the deficiency in the supply of oxygen, the formation of toxic reduction compounds in the soil, the prevention of bacterial processes essential to the growth of higher plants, or the inability of the crop to secure adequate amounts of nutrients from the soil.

THE OPTIMUM AIR SUPPLY

Ordinarily, the optimum conditions for the growth of crop plants obtain when about one-third the pore space of the soil is occupied by air, the remainder being taken up by water. It has been found that the rate of diffusion of gases through soils is independent of their texture and structure, but is approximately proportional to the square of that part of their pore space that is occupied by air. Thus, if the air space is cut in half, the rate of diffusion of the carbon dioxide from the soil to the air above is reduced to one-fourth. As the process of diffusion is slowed down, a point of accumulation of carbon dioxide may finally be reached at which the plant can no longer excrete this compound into the soil. Meanwhile, anaerobic processes of decomposition may have gained the ascendency in the soil, with the results indicated previously.

An interesting study of the effect of differences in the moisture supply, and accordingly of the air supply, of soils is reported by Greaves, who measured various bacterial activities in soils to which had been added supplemental increments of water up to complete saturation. Under these conditions, determinations were made of the rates of accumulation of ammonia and nitrates, and the rate of nitrogen fixation by non-symbiotic bacteria, by the usual methods of procedure in such studies. The data are given on the comparative basis, from which it can be seen that the optimum conditions for these various bacterial activities are at a moisture content of about 60 per cent of saturation for ammonifying and nitrifying bacteria and at a somewhat higher percentage for the nitrogen-fixing bacteria.

TABLE 41

AIR AND WATER SUPPLY OF SOILS IN RELATION TO BACTERIAL ACTIVITIES* (GREAVES)

Percentage Saturation	Ammonia Production	Nitrate Accumulation	Nitrogen† Fixation
10	2	11	30
20	8	17	25
30	32	31	25
40	68	62	38
50	85	85	45
60	100	100	75
70	78	40	100
80	57	9	90
90	49	0	45
100	45	0	25

* Calculated in relative terms, the point of highest efficiency being given a value of 100.

† Nitrogen fixation by non-symbiotic bacteria.

There has been a considerable amount of investigation as to the optimum moisture supply for crops when grown under irrigation. The accompanying example is illustrative of data that have thus been secured. The water in these tests was applied at weekly intervals during the growing season, the total amounts that were added being as indicated. The rainfall during the crop season amounted to 17.42 inches. This quantity must be subtracted from the number of acre-inches of water shown in Table 42 to determine the amounts of irrigation water that were supplied.

TABLE 42

The Critical Point in the Water Supply for Corn (Harris)

Water Added, Acre-inches	Grain, Bu.*	Stover, Cwt.*	Bushels of Grain per Inch of Water
17.42†	75.9	78.4	4.35
22.42	91.4	89.7	4.08
27.42	92.5	85.0	3.37
37.42	99.1	97.1	2.65
47.42	95.7	95.4	2.02
57.42	90.0	90.0	1.57

* Six-year average acre yields with irrigation.

† This figure is the average yearly rainfall which occurred during the period of the experiment.

The law of diminishing returns is in operation in the above test, but the critical point in the water-and-air relationships is also apparent with the heaviest applications of water.

AERATION OF CULTURE SOLUTIONS IN RELATION TO PLANT GROWTH

If all the pore space in soils is filled with water, the crop plants growing on them soon die. On the other hand, it is common practice

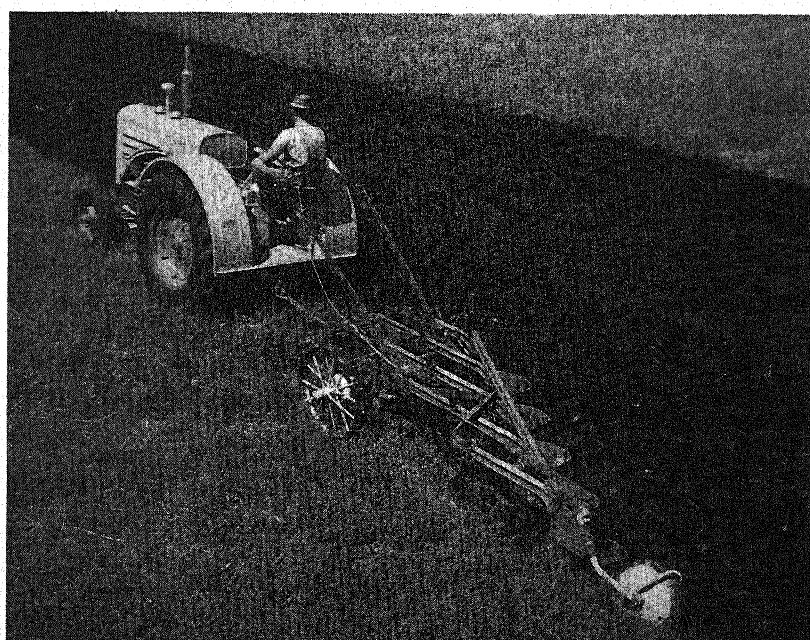

Fig. 14. Plowing and cultivating aerate the soil and stimulate bacterial action, with resulting loss of organic matter.

in investigational studies to grow corn, wheat, and similar plants in culture solutions. With these plants, however, it is necessary to aerate the solutions by forcing air through them from time to time. The effect of this aeration on the rate of growth of plants is shown in Table 43. Under such conditions, land plants are far removed from their natural environment. Nevertheless, it is probably safe to assume that even better effects would be observed under field conditions if, when the soil was waterlogged, a similar method of aeration could be put into operation. In the latter case, aeration would have the additional benefit that it would tend to prevent the formation of reduction compounds resulting from anaerobic decomposition by soil bacteria.

Plant roots differ considerably in their aeration requirements. It has been shown that buckwheat, a plant that grows satisfactorily on somewhat wet and acid soils, is not nearly as sensitive to the lack of aeration in the culture solution as is barley. On the other hand, when carbon dioxide is forced through the culture solutions, all plants, including buckwheat, soon wilt.

TABLE 43

Effect of Aeration of Culture Solutions on Plant Growth (Hall)

Treatment	Weight in Grams per Plant	
	Barley	Lupines
Non-aerated	1.31	0.83
Continuously aerated	2.12	1.53

THE COMPOSITION OF SOIL AIR

The soil air differs in composition from that of the atmosphere in that it contains less oxygen and more carbon dioxide. The normal concentration of carbon dioxide in the atmosphere is 0.03 per cent by volume. In the soil, its concentration often exceeds 1 per cent and, in exceptional instances, has been found to be as high as 15 per cent. The content of carbon dioxide fluctuates considerably through the season, depending upon the climatic and soil conditions as they affect the activities of soil bacteria and the growth of crops. The table on page 95 is of interest in this connection.

It is believed by some investigators that the increased concentration of the carbon dioxide in the soil air which occurs during the growing season is fairly definitely correlated with the rate of growth of the crop, and that it is in considerable part due to the respiration of plant roots. There seems to be evidence in favor of this conclusion in Table 44.

Thus, the wheat crop probably began to grow well in November, was retarded for a time during the cold weather of December and January, but came on more rapidly in the spring, with maximum growing activity

TABLE 44

PERCENTAGE COMPOSITION OF THE SOIL AIR* DURING A YEAR (RUSSELL)

Date	Manured Plot		Unmanured Plot		Inches† Rain-fall	Degrees C.	
	CO_2	O_2	CO_2	O_2		Air	Soil
Feb. 11	0.55	18.97	0.13	19.86	0.60	8.3	....
Mar. 13	0.46	20.18	0.21	20.53	0.22	3.9	....
Apr. 14	0.65	19.70	0.22	20.64	0.68	1.7	....
May 13	1.45	19.42	0.35	20.53	0.56	10.5	11.1
June 3	0.42	20.56	0.50	20.77	0.35	13.9	17.4
July 11	0.35	20.66	0.29	20.79	0.42	15.0	15.5
Aug. 29	0.24	20.70	0.22	20.73	0.24	19.4	18.1
Sept. 22	0.17	20.79	0.11	20.83	0.52	14.4	13.3
Oct. 6	0.18	20.81	0.16	20.82	0.41	11.1	12.9
Nov. 10	0.54	20.72	0.35	20.56	0.21	5.0	6.5
Dec. 22	0.34	20.45	0.25	20.35	0.13	2.8	4.5

* Soil from Broadbalk Field, continuous wheat, at Rothamsted.

† During previous seven days.

and respiration in May. On the other hand, there is a fairly definite cycle of activities of soil bacteria which reaches its maximum and minimum points at about the same periods as those indicated by the percentage of carbon dioxide in the soil air.

SOIL AERATION IN RELATION TO PLANT GROWTH

Root hairs are developed in abundance under conditions of adequate aeration but they may be almost entirely absent in waterlogged or poorly aerated soils. Since the absorption of water and of soil nutrients takes place in large part through the root hairs by reason of the extensive surface areas which they expose, it is apparent that there may be, within limits, a very definite relationship between the conditions as to aeration of the soil and the rate of growth of plants.

Subsoils, as a rule, contain higher percentages of carbon dioxide than do surface soils. They are often more compact, they usually contain larger amounts of water, and the rate of diffusion of gases in them is slower. It is because of this that, in some soils and with certain plants, the distribution of the roots is largely confined to the better-aerated portions of the surface soil. Those roots that penetrate very compact layers of subsoil are probably not very efficient absorbers, except at points of adequate aeration, because of the lack of development of root hairs. Once they have penetrated to considerable depths, they pave the way for larger yields of the following crops by reason of the better aeration of the subsoil through the channels left behind when the roots decay. The good effects of alfalfa and sweet clover may have their explanation in part in this fact. Earthworms are probably of considerable importance also in this connection.

THE TOXIC-EXCRETION THEORY

Of the many explanations that have been offered for the loss of productivity of soils under certain conditions, one of the oldest is that which assumes that plants excrete toxic substances into soils. While both organic and inorganic substances that are toxic to plants have been isolated from soils, the problem is to determine their origin. They may have been excreted by plants, or they may have been formed as a result of decomposition processes taking place in the soil. The evidence along this line points in the direction of the latter. In so far as is known, the only excretory product of plants that might have any toxic effect is carbon dioxide. Any organic toxicity that may develop in soils is probably the result of anaerobic decomposition in the absence of supplemental oxidation by aerobic bacteria. It is conceivable that a considerable number of reduction compounds might be produced under certain conditions in soils, and that these compounds, if allowed to accumulate, would be toxic not only to plants but to soil bacteria as well.

THE SIGNIFICANCE OF COLOR IN SOILS

Of particular interest in connection with possible toxicity in soils, resulting from insufficient aeration, is their color. In well-drained soils, the compounds of iron are oxidized to the ferric state as indicated by their red, yellow, or brown colors. In the absence of good drainage, the subsoil is often of a blueish, gray, or mottled color, indicating the presence of reduction compounds. Under a manure heap, the soil is usually of a blueish-green cast. The reduction is brought about as a result of the decomposition of organic matter under anaerobic conditions. Peat soils, located in swamps, are black or brown in color, depending upon the nature of the processes of decomposition as related to the air supply and the presence or absence of carbonate of lime in the leachings from the surrounding higher levels.

The presence of ferrous compounds in the subsoil is indicative of reducing conditions that are unfavorable to the growth of aerobic bacteria and to crop plants. Ferrous sulfate is known to be toxic to plants. It is used as a spray for the eradication of such weeds as mustard and dandelions. It seems probable that, if the subsoil contains this and similar compounds, the development of plant roots will be hindered. Farmers have learned to judge the quality of soils by their color, and with considerable accuracy, as might be expected from the relationships indicated above.

It will be evident that some soils have inherited their color from the parent rock. A red shale will produce a red soil even though the conditions as to aeration are not particularly favorable to the development of such a color. The red shales were formed from red clays that were deposited on the ocean floor. No reduction of their iron compounds could take place in the absence of decomposing organic matter or other reducing agents. Subsequently, when they were elevated above the surface of the ocean, they were still red and gave rise to soils of the same color unless reduction processes interfered.

AIR SUPPLY IN RELATION TO SEED GERMINATION

Seeds differ considerably in their oxygen requirements for germination. Among those that seem to require considerable amounts of oxygen are the seeds of corn, oats, wheat, cabbage, melons, peas, and beans. On the other hand, it has been shown that the seeds of timothy, bluegrass, lettuce, carrots, white clover, red clover, sweet clover, and alfalfa will germinate under water, a condition in which the supply of oxygen is confined to that dissolved in the water. White clover seeds have been germinated under water covered with paraffin oil, although they will not germinate in a vacuum. In general, the larger the seeds the greater the amount of oxygen required for their germination.

AEROBIC AND ANAEROBIC DECOMPOSITION

Bacteria are classified into three general groups, depending upon their oxygen requirements. These groups are known as the aerobes, facultatives, and anaerobes. In a manure heap, the supply of oxygen in the interior is quite limited, while on the exterior it is abundant. Representatives of all three groups of bacteria are at work in the decomposition processes. If the conditions are highly favorable for aerobic decomposition, "firefanging" may result. The anaerobic processes are primarily to be desired in the manure heap since, under such conditions, the cellulose materials are gradually decomposed without abnormal rise in temperature and the processes of hydrolysis and mineralization are effected without loss of nitrogen through volatilization.

The same processes are in operation in the soil. Here, however, the end products are consumed by higher plants which, for the most part, require their food materials in a highly oxidized state. If the conditions in the soil are too largely anaerobic, as would be the case if the soil contained excessive amounts of water or large quantities of rapidly decomposing carbonaceous substances, then nitrates may be reduced to nitrites or even to free nitrogen, sulfates to sulfides, and ferric and manganic compounds to the ferrous and manganous states, with resulting crop injury.

NITRATE REDUCTION IN SOILS

Ordinarily, nitrates are not produced in manure piles, the nitrogen being present largely as hydrolysis products of proteins, as urea, and as ammonium carbonate, or being contained in the reconstructed proteins of bacterial bodies. When manure is added to the soil, the process of oxidation is carried forward to completion, with the formation of nitrates. Crop plants utilize nitrates apparently in preference to other forms of nitrogen, as is shown by the almost immediate growth effects following applications of nitrate of soda.

It has been frequently observed that nitrates disappear from soil under conditions of saturation with water or when large amounts of highly carbonaceous materials are incorporated with them. The explanation may be found in the activities of anaerobic denitrifying bacteria, which secure their oxygen by the reduction of such compounds as nitrates, or in the utilization of these nitrates by the soil bacteria for protein construction in their own bodies. The incorporation of large amounts of easily decomposable organic matter in soils brings about a rapid multiplication of the bacterial population, with a resulting increased demand for available nitrogen.

DENITRIFICATION IN SOILS

A number of different species of bacteria have been isolated from soils that have the power of liberating nitrogen gas from nitrates. The species name commonly applied to these bacteria is *B. denitrificans,* although a number of species of bacteria known by reason of other functions are able to effect the same change. *Thiobacillus denitrificans* is of interest in this connection because of its reducing action on sulfates. Laboratory experiments show that nitrates disappear quite rapidly from soils that are saturated with water. For this reason, sulfate of ammonia is preferred to nitrate of soda as a nitrogen fertilizer for paddy rice.

It is possible that denitrification may also occur as a result of the use of very large amounts of manure, even though it be well rotted. The excessive evolution of carbon dioxide may cause the development of anaerobic conditions in the soil. On the other hand, it seems probable that copious evolution of carbon dioxide from the soil will increase the rate of growth of plants by reason of the increased supply of this gas at the disposal of their leaves. This may in part explain the better crop yields that are produced on soils rich in organic matter as well as on those that are liberally manured.

THE SOLUTION EFFECTS OF CARBON DIOXIDE

While excessive amounts of carbon dioxide are injurious, its presence in the soil is necessary as a means of hastening the solution of soil minerals. One of the classic experiments is that which shows the etching effect of plant roots on a marble slab, presumably as a result of the action of the carbon dioxide excreted by the root hairs. Carbon dioxide also serves as an effective buffer in soils and aids in the prevention of excessive acidity or alkalinity. It seems probable, however, that the excretions from plant roots are adequate sources of supply of carbon dioxide in productive soils, and that little additional advantage is gained from the carbon dioxide that is liberated from the decay of green manures and other readily decomposable organic substances.

EFFECT OF EXCESSIVE AERATION ON SOILS

The rate of exchange of gases between the atmosphere and the soil is so rapid in coarse-textured soils that excessive oxidation of the organic matter in them may occur. The difficulty is especially pronounced in sandy soils that are under clean cultivation and are located in warm latitudes. Under such conditions, the losses of nitrogen and mineral nutrients are very rapid and the water-storing capacities of soils are very much reduced. Such soils are highly productive if adequate amounts of organic matter can be maintained in them, or if the moisture and mineral requirements of the crops can be met by irrigation and the use of fertilizers. This is in marked contrast to the conditions that obtain in swamps, in which the soil may be almost entirely plant refuse. Such soils are named mucks or peats.

CARBON DIOXIDE EVOLUTION AS A MEASURE OF PRODUCTIVITY

It has been shown that the rate of evolution of carbon dioxide from soils, when incubated under certain standard conditions, is a fair index of their productivities. This process can also be used as a measure of the effectiveness of any contemplated treatment to which the soil is to be subjected. There is a fairly good correlation between the crop-producing capacity of a soil, the rate at which ammonia is produced in it when nitrogen is added in readily available organic forms, the rapidity with which nitrates accumulate, and the quantity of carbon dioxide that is evolved.

SOIL MANAGEMENT IN RELATION TO AERATION

Ordinarily, the problem is one of increasing the rate of renewal of the air in soils in order to prevent the accumulation of carbon dioxide and the formation of reduction compounds. The oxygen supply of soils is renewed not only by diffusion, but also by processes of ventilation which occur as a result of temperature changes or of the movement of water in them. The latter is particularly important since it may effect an almost complete replacement of the soil air and its subsequent renewal as the water is lost by drainage, evaporation, and transpiration. It is in the absence of free movement of water, particularly with the fine-textured soils, that the rate of renewal of the air is inadequate. The use of tile, the growing of deep-rooted crops, and the incorporation of large amounts of organic matter with the soil are effective means of improving the aeration. Cultivation may be of some value in this connection. Deep plowing and subsoiling have been recommended. The use of dynamite has been suggested for very impervious subsoils. Something can be done in the selection of crops that are adapted to such conditions. Improving the mechanical condition of soils and their subsoils, as related to the movement of water and air through them, is one of the fundamental problems involved in their successful management.

Recently, considerable attention has been given to the comparative yields of crop plants when grown in soil, in pure sand that is watered with a nutrient solution, and in the nutrient solution in the absence of sand. The evidence indicates that higher yields can be produced in sand culture than in soil or in solution culture. The usual procedure in sand culture is to flood the sand with the nutrient solution and then to allow the solution to drain back into the storage tank. By repeating this process at suitable intervals, the conditions relative to the supply of air, moisture, and nutrients can be made almost ideal. This points to the probability that the yield of crops, when grown on soil, could be materially increased if some improved means of ventilating the soil could be put into effect. The above-mentioned mechanical means of aerating soils ought to be re-examined for the purpose of improvement. The use of a subsoiling device, to break up the plow sole or hardpan, and the use of gypsum in this opening, to develop granulation of the soil particles, merit consideration in this connection.

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CHAPTER X

THE SOIL SOLUTION

When plants are grown in culture solutions, it is necessary to control, within somewhat narrow limits, the total concentration of the salts in solution, the reaction of the solution, and the ratios in which the nitrogen and mineral nutrients are present. These requirements are undoubtedly also met in productive soils. Unfortunately, it is difficult to determine the exact nature of the solution with which the roots of plants are in contact in the soil. Various methods of displacement have been employed, with the result that some idea of the concentrations of the several elements in soil solutions has been gained. There is, however, a fundamental difference between soil solutions and culture solutions. The soil solution is in very close contact with the undissolved mineral complex which tends to renew the solution as elements are removed from it by plants. Furthermore, root hairs adhere very closely to particles of soil. The concentration of the solution which immediately surrounds these particles may be quite different from that of the main body of soil solution.

ALKALI SOILS

In regions in which the rainfall is so limited that the loss of water through drainage is practically negligible, substances which have been dissolved from the soil may accumulate, under certain conditions, in the form of soluble salts. These salts may have had their origin in place or they may have originated at some other point and been carried to their present location by water, either through seepage from surrounding higher levels or by overflow at some earlier period in their history. Whatever their origin, it is found that they are made up of the carbonates, chlorides, sulfates, and nitrates of sodium, potassium, calcium, and magnesium. The relative amounts of these salts vary considerably from place to place, as is shown in Table 45.

ALKALI TOLERANCE OF CROPS

The accumulation of these salts, commonly called *alkali*, interferes with the growth of plants by reason of their abnormally high concentration, their alkalinity, or the unfavorable ratios in which the various

TABLE 45

PERCENTAGE COMPOSITION OF ALKALI FROM DIFFERENT STATES (HARRIS)

Salts	Colorado	California	Washington	Montana		Arizona	
				*	†	*	‡
KCL	1.64	....	5.61	....	....	4.00	22.10
K_2SO_4	....	3.95	....	1.60	21.41	....	....
K_2CO_3	....	....	9.73	....	....	....	....
Na_2SO_4	....	25.28	....	85.57	35.12	....	....
$NaNO_3$	33.07	19.78	....	....	....	....	....
Na_2CO_3	....	32.58	13.86	....	7.28	....	....
NaCl	6.61	14.75	....	0.55	....	81.15	13.77
Na_2HPO_4	....	2.25	....	....	....	....	....
$MgSO_4$	....	....	....	8.90	4.06	....	....
$MgCl_2$	12.71	....	....	....	....	7.71	3.98
$CaCl_2$	17.29	....	....	....	....	0.25	....
$NaHCO_3$	....	....	36.72	0.67	22.06	0.28	21.02
$CaCO_3$	21.48	....	1.87	2.71	10.07	6.61	32.25
$Ca(HCO_3)_2$	....	....	16.48	....	....	....	....
$Mg(HCO_3)_2$	....	....	15.73	....	....	....	....
$(NH_4)_2CO_3$	....	1.41	....	....	....	....	....

* Crust. † 0–10 inches. ‡ 0–72 inches.

FIG. 15. A large salt deposit at Searles Lake, California, that is now being worked for potash by the American Potash and Chemical Corporation.

elements are present. If the salts are largely sulfates and chlorides, the surface incrustations are white. If the alkali carbonates are present in considerable amounts, the soil becomes brown or black in color by reason of the dissolving of the humus substances. This *black alkali* becomes toxic to plants at much lower concentrations than does the *white alkali*, since it has the additional property of high alkalinity.

As would be expected, plants differ considerably in their capacities to endure alkali. Among the more resistant crop plants may be mentioned alfalfa, sweet clover, millet, sorghum, rape, barley, rye, sugar beets, asparagus, and cotton. Of the fruits, the date palm and the grape are perhaps the most tolerant. The capacity of plants to withstand alkali is determined not only by its concentration, its reaction, and the ratios of its constituent elements, but also by its distribution in the soil. Deep-rooted plants may grow satisfactorily if the alkali is concentrated in the surface soil, while shallow-rooted crops grow best when the alkali salts are located at greater depths.

THE CONTROL OF SOIL ALKALI

Methods of control depend upon the nature of the alkali and the location of the soil with reference to supplies of irrigation water. With black alkali, applications of sulfur and calcium sulfate may suffice. Sulfur, when oxidized to sulfuric acid, neutralizes the alkali. The calcium of calcium sulfate replaces the sodium in the exchange complex, and provides for its removal from the soil by heavy irrigation and drainage. If the alkali salts have accumulated on the surface of the soil, they may be removed by scraping or they may be plowed under to a considerable depth.

It is of interest to note that alkali became apparent in some localities only after irrigation had been practiced for several seasons. The soluble salts, which previously had been deposited at lower depths or were fairly well distributed through the soil and subsoil, were carried upward by the water as it moved to the surface. A part of the water was lost by evaporation, thus leaving the soluble salts as surface deposits. It has also been found that quantities of salts that can be tolerated by crop plants when the soil is at its optimum water content become injurious when the percentage of moisture is reduced between irrigations. For these reasons, it is necessary to give consideration to such matters as the rates and times of application of irrigation water and to such tillage and other operations as have to do with the reduction in loss of water by surface evaporation. The alkali soil problem is much more difficult than is that of acid soils, although the area over which alkali is a limiting factor in crop growth is much less than that included in the humid regions where acid soils are the rule.

ACID SOILS

In humid regions, the soluble salts that are formed by the decomposition of the soil minerals are gradually removed in the drainage waters. Their accumulation is thus prevented. Evidence of their removal is to be found in the enormous deposits of limestones, common salt, and potash salts that are widely distributed over the earth. The composition of ocean water is of significance in this connection. It has been estimated that the total amount of salts in the ocean is sufficient to cover the entire surface of the United States, including Alaska, to a depth of 1.6 miles. The average salinity of the ocean waters is about 3.5 per cent. These salts are composed of various elements in the percentages indicated in Table 46.

TABLE 46

Percentage Composition of Oceanic Salts (Clarke)

Material Present	Atlantic Ocean	Gulf of Mexico	China Sea	Black Sea	Mediterranean Sea
Cl	55.18	55.24	55.34	55.12	55.11
Br	.17	.17	.13	.18	.19
SO_4	7.91	7.54	7.76	7.47	7.89
CO_3	.21	.34	.03	.46	.20
Na	30.26	30.80	30.67	30.46	30.64
K	1.10	1.10	.97	1.16	1.09
Ca	1.24	1.22	1.19	1.41	1.23
Mg	3.89	3.59	3.75	3.74	3.65
Salinity*	3.63	3.54	3.20	....	3.87

* Percentage content of salts in water.

The ocean sediments are very rich in calcium and magnesium carbonates, of which it is estimated that over 2 billion tons are being deposited annually. In addition, nodular deposits of manganese and of phosphates and beds of the potash mineral glauconite are widely distributed over the ocean floor.

The continuation of the leaching process that takes place in the formation of soils in humid climates and the removal of these soluble salts result in the accumulation of a relatively insoluble soil residue which is made up largely of silicon, aluminum, and iron in the form of their hydrated oxides or the silicate combinations of these oxides. In addition, such silica as exists in the form of quartz tends to remain as such because quartz is very resistant to weathering. The decay of organic matter, with the resulting liberation of carbonic, nitric, and sulfuric acids, hastens the process.

THE NATURE OF SOIL ACIDS

The gradual removal from the soil of the alkalies and alkaline earths results in the accumulation of a potentially acid residue. This is made up normally of about 75 per cent silica, 10 to 15 per cent oxides of iron and aluminum, some combined water, some organic matter, and smaller percentages of various other oxides. Some idea of the nature of these silicate residues may be obtained from a study of the following outline of the processes involved in the weathering of orthoclase, a primary soil mineral.

TABLE 47

STAGES OF WEATHERING OF ORTHOCLASE (VAN HISE)

$2KAlSi_3O_8 + H_2O + CO_2$	$= K_2CO_3 + 2HAlSi_3O_8$	(" orthoclasite ")
$2HAlSi_3O_8 - SiO_2$	$= H_2Al_2Si_4O_{12}$	(pyrophyllite)
$H_2Al_2Si_4O_{12} + H_2O - SiO_2$	$= H_4Al_2Si_2O_9$	(kaolinite)
$H_4Al_2Si_3O_9 - 2SiO_2$	$= H_4Al_2O_5$	(bauxite)
$H_4Al_2O_5 + H_2O$	$= H_6Al_2O_6$	(gibbsite)
$H_4Al_2O_5 - H_2O$	$= H_2Al_2O_4$	(diaspore)

SECONDARY SOIL MINERALS

By the application of petrographic and X-ray techniques, it has been shown that the residues of the primary minerals, of which orthoclase is one example, consist of definitely crystalline secondary minerals. Of these secondary minerals, the two best known are the *kaolinites* and the *montmorillonites*. The crystal lattices of the kaolinite group, with a general formula $Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O$, are made up of 1 sheet of silica to 1 sheet of alumina; while those of the montmorillonite group, with a general formula of $Al_2O_3{\cdot}4SiO_2{\cdot}5H_2O$, contain 2 sheets of silica to 1 of alumina. The kaolinite lattices are fixed and only their outer surfaces are reactive, whereas those of the montmorillonites are an expanding type, subject to a high degree of hydration and reactivity both on the surface and within the crystals. The primary silicate minerals, still remaining in the silt and coarser separates of the soil, exist largely as central cores in the soil grains, surrounded by colloidal films of these secondary silicates and by hydrous oxides and humates of iron and aluminum.

The climate is the dominating factor in determining the nature of the decomposition products of the primary minerals — kaolinites being most prominent in the lateritic soils; and montmorillonites, in the podsolic, chernozem, and desert soils. Secondary silicates and the associated humates have such slight solubilities that they cannot develop a high degree of acidity. Nevertheless, they possess the capacity to adsorb large quantities of bases before the neutral point is reached.

THE INTENSITY FACTOR IN SOIL ACIDITY

Four types of acids are found in all acid soils: hydrated silicates, mineral acids, organic acids, and carbonic acid. Of these, by far the most abundant are the acid silicates, of which kaolinite has been mentioned as a typical example. Such silicates are not highly soluble. Their acidity is, therefore, potential rather than active. In fact, the soil has a base-adsorbing capacity long before the soil solution becomes acid in reaction. The soil, meanwhile, is being washed with rainwater carrying small amounts of such strong mineral acids as nitric and sulfuric, in addition to its usual content of carbonic acid. Additional nitric acid is being contributed by the nitrification of nitrogen which has been accumulated by nitrogen-fixing bacteria. As the acidity develops, iron and aluminum are found in the soil solution. These, it may be assumed, are present as the nitrates or sulfates. Such salts, on hydrolysis, yield hydrogen ions to the soil solution, since they are combinations of relatively weak bases and strong acids.

A third group of acids, which are of minor importance in inorganic soils, but are of especial interest in muck and peat soils, may be classified as organic. The more complex of these are ordinarily given the name of *humic acids* and are of rather indefinite composition. Of more importance from the point of view of the development of acid soil-solutions are the somewhat simpler organic acids, of which butyric, lactic, and acetic are common examples. These have their origin in the decomposition of organic matter but are readily oxidized by molds, with the formation of carbon dioxide and water. The fourth type of acid is found in carbon dioxide, which is always present in the soil water, having its origin in the respiration of plant roots and in the decomposition of soil organic matter.

In acid soils, therefore, both the capacity and the intensity factors are involved. The former is of great importance in determining the lime-adsorbing power of a soil. The latter determines the type of plants that can be grown in the soil as it is. The intensity is known to be a function both of the solubility and of the degree of ionization of acids. Ionization of an acid is measured in terms of what is known as its *hydrogen-ion concentration.* This is ordinarily stated in terms of

pH, which is the common logarithm of the reciprocal of the hydrogen-ion concentration expressed in terms of normality.[1] Pure water, free from carbon dioxide, has a pH of 7, which means that it is a $\frac{1}{10,000,000}$ normal solution of hydrogen and also of hydroxyl ions. A solution having a pH of 5 contains 100 times as many free hydrogen ions as does water. One with a pH of 8 contains 10 times as many hydroxyl ions as are found in the same volume of pure water. The pH of water suspensions of the soils of humid regions ordinarily ranges from 4 to 8, usually being less than 7.

ACID TOLERANCE OF CROPS

Experience has shown that, with an increase in the acidity of soils, plants having a high lime requirement — such as sweet clover, alfalfa, lettuce, spinach, beets, onions, and many others — will not grow satisfactorily unless the soil is limed. With greater increase in acidity, it becomes necessary to substitute less and less desirable crops until a point is reached at which few of those commonly grown will thrive. Further complications arise by reason of the injurious effect of the acid soil on certain essential soil bacteria, particularly those that function in the processes of nitrogen fixation and nitrification.

It has also been shown that acid soils are injurious to crops and to soil bacteria in certain indirect ways. As the acidity of soils increases, the concentration of aluminum in the solution also increases. This element seems to be toxic to certain crop plants in the concentrations in which it exists in acid soils. Barley and rye are injured to about the same degree by increasing the acidity of the nutrient solution, but the latter is much more tolerant of soluble aluminum. Any crop to which aluminum in dilute concentrations is toxic will have difficulty in growing on an acid soil. The disease known as *root rot* of corn is associated with an accumulation of aluminum in the nodal tissues of the corn plants.

THE CONTROL OF SOIL ACIDS

The usual method of controlling the acidity of soils is by the use of lime in the oxide, hydrate, or carbonate form. Draining an acid soil is also effective in preventing the accumulation of soluble acid salts. There are possibilities in the choice of fertilizer materials, which vary from those that leave an acid residue to those that have a markedly alkaline effect. The incorporation of large amounts of organic matter in the soil is of some value, principally because of its buffer action. It

[1] A normal hydrogen-ion solution contains 1 gram of dissociated acid hydrogen per liter.

is also possible to choose crops that are not particularly sensitive to acid soil conditions, of which soybeans, oats, rye, alsike clover, red top, peanuts, watermelons, blueberries, and cranberries are good examples. Fortunately, soluble acids or acid salts do not accumulate to any large extent in soils since the same agency which caused the loss of the alkalies and alkaline earths serves to rid the soil of these as well.

OPTIMUM RATIOS OF THE ELEMENTS IN NUTRIENT SOLUTIONS

In alkali soils, the problem is largely one of excessive concentration of salts in the soil solution. In acid soils, the reaction of the soil solution is often a limiting factor in crop growth. But, even if both these factors are under control, there remains to be considered the ratios in which the elements are yielded up by the soil to the plant. It has been shown that the ammonium, magnesium, sodium, and potassium ions, in the order named, are injurious to plants when supplied, singly, as salts to culture solutions. This injurious effect may be overcome by the addition of salts of other basic elements, of which those of calcium are most effective. One of the difficulties apparently lies in the fact that the pectates of all the other basic elements are more soluble than is that of calcium, which ordinarily makes up a large portion of the middle lamella of the cells. In the absence of adequate amounts of calcium in the nutrient solution, there is a substitution of other basic elements. Potassium pectate is readily soluble in water, and even magnesium pectate is much more soluble than the corresponding calcium salt. As a result, the permeability of the cell wall is altered and the cell tends to lose its protoplasmic contents to the nutrient medium. The other essential elements in the solution are of little use to the plant unless the calcium ion is present in sufficient amount to satisfy the normal needs of the plant in the construction of its cell walls.

CULTURE SOLUTIONS FOR PLANTS

The widespread use of culture solutions for growing plants for research purposes finally led to a consideration of their possibilities in practical agriculture. It was soon demonstrated that most of the common crop plants could be grown to maturity and made to produce marketable crops without the use of soil. These findings are now being put into effect on a good-sized scale in the production of carnations, roses, chrysanthemums, tomatoes, and a number of other plants as market commodities. The water-culture system, now known as *hydroponics,* has even been applied to the production of potatoes, wheat, and corn. In its more modern form, use is commonly made of non-calcareous sand or gravel as an agent for anchoring the roots of plants.

An example of the type of salt mixture that is employed in making up such a nutrient solution, chosen from a recent publication of the Indiana Experiment Station, is shown in the following table.

TABLE 48

NUTRIENT SOLUTION FOR PLANTS GROWN IN WATER CULTURE (WITHROW)

Salts (Fertilizer-grade Chemicals)	Pounds	Ounces
Magnesium sulfate (anhydrous)	0	9
Treble superphosphate (0–48–0)	1	6
Potassium nitrate (13–0–44)	9	12
Calcium sulfate (gypsum)	6	10
Ammonium sulfate (10–0–0)	1	4
Total in 1000 gallons of water	19	9

TRACE ELEMENTS REQUIRED BY PLANTS

In addition to using the ordinary fertilizer salts, it is necessary to make supplemental use of small quantities of certain of the less commonly mentioned plant food elements, of which iron, manganese, zinc, and boron are the most important. Suggestions for supplying these trace elements are given below.

TABLE 49

TRACE ELEMENTS REQUIRED FOR CULTURE SOLUTIONS (SHIVE)

Chemicals	Quantities*
Boric acid	0.8 gram
Manganese sulfate	0.8 gram
Zinc sulfate	0.8 gram

* These quantities are dissolved in 1 pint of water, and 10 milliliters (2 teaspoonfuls) are added to every 5 gallons of culture solution. In addition, 100-milliliter portions of a solution of ferrous sulfate, made by dissolving 0.8 gram of the salt in 1 pint of water, are added to the culture solution, from time to time.

The sand or gravel is placed in watertight benches, and the solution is pumped into it and allowed to drain out at regular intervals for aeration purposes. The *p*H of the solution is kept under control by the use of acids and alkalies, at a point best suited to the particular plant being grown.

It now seems probable that the production of plants without the use of soil may assume, in time, large proportions, particularly in the growing of flowers and certain types of vegetables. There are a number of important advantages in this type of culture. The nutrient supply of the plant can be altered at will. Flowering and fruiting can be advanced or delayed, according to market demands. Diseases are more readily controlled. In proportion as our knowledge of the needs of the several species of plants is advanced, the use of sand and gravel cultures is certain to increase, particularly in greenhouse production.

THE SOIL SOLUTION IN HUMID CLIMATES

These illustrations of culture solutions are given for the purpose of comparison with the solutions that have been extracted from soils. Of the various methods that have been employed to secure such solutions, those of displacement by water, alcohol, and oil are in common use. There is some question whether the solutions thus secured are actually the same as those with which the root hairs of plants are in contact. Nevertheless, they are of value for comparative purposes in relation to the known productivities of soils. Table 50 gives some data from water extractions of a group of soils having the same physical characteristics and belonging to the same series, but of varying degrees of productiveness.

TABLE 50

WATER EXTRACTS OF SOILS* IN RELATION TO THEIR PRODUCTIVITIES (BURD)

Productivity		Seasonal Averages of Water Extracts — Parts per Million				
General	Barley†	K_2O	CaO	MgO	P_2O_5	NO_3
Good	88.4	57	127	40	12	146
Good	86.5	48	48	38	5	131
Good	84.0	66	52	25	3	120
Medium	70.4	54	118	43	7	141
Poor	56.2	52	45	23	5	88

* Silty clay loam soils of the same series.
† Yield in bushels per acre.

In addition to those listed above, the Cl, SO_4, and CO_3 ions and traces of some of the rarer elements are always present in soil solutions. In acid soils the Fe, Al, and Mn ions will also be found. One is impressed with the low concentrations of the nutrient ions in these soil extracts. It is well to keep in mind that the solution is in contact with the mineral complex of the soil, which serves to renew it as the nutrient elements are removed by crops or are lost in the drainage water. The rate at which this renewal takes place is an important factor in determining the productivity of a soil.

COMPARISON OF COMPLETE ANALYSES WITH WATER EXTRACTIONS

While complete analyses of soils are of considerable interest and value, there is some question as to their usefulness in determining either the present or potential productivities of many soils. This is indicated in the following data, in which are shown the comparative amounts of the several materials that are found by the various methods of soil analysis that have enjoyed considerable popularity at different periods in the history of soil and plant science. It will be noted that both the good and poor soils contain about the same total amounts of the several oxides, but that they differ considerably in the nutrient contents of their water extracts.

TABLE 51

COMPARISON OF VARIOUS METHODS OF ANALYSIS OF SOILS (BURD)

Percentages of	K_2O	CaO	MgO	P_2O_5	NO_3
Good Soil:					
Complete analysis — fusion	1.98	1.48	2.66	0.23	....
Acid digestion — HCl 1.115	1.05	1.43	2.46	0.22	....
Acid extraction — 1% citric	0.04	0.45	0.22	0.10	....
Water extractions — p.p.m.*	57	127	40	12	146
Poor Soil:					
Complete analysis — fusion	1.85	1.50	3.57	0.21	....
Acid digestion — HCl 1.115	0.89	1.48	3.32	0.20	....
Acid extraction — 1% citric	0.04	0.42	0.14	0.07	....
Water extractions — p.p.m.*	52	45	23	5	88

* Seasonal averages.

SOIL MANAGEMENT IN RELATION TO THE SOIL SOLUTION

Although it is now possible to determine what constitutes an optimum culture solution for crop plants when grown in water cultures, such information is of very little direct value in its application to the problem of the soil. This is so because the soil tends to exercise precipitation and adsorption effects which immediately alter the ratios in which the ions exist in any solution that might be applied. Numerous other complications are involved. Nevertheless, a large part of the farmer's efforts have to do with the problem of controlling the soil solution within such limits as may permit of the growing of satisfactory yields of crops. Growing clover, using manure, applying lime and fertilizers, and cultivating the soil, all influence the composition of the soil solution.

The good or bad effects of these practices, to be correctly interpreted, must take into consideration all three properties of nutrient solutions, viz.: concentration, reaction, and ion ratios. Sulfate of ammonia supplies nitrogen to the soil solution, but it also affects its reaction. Superphosphate supplies the elements phosphorus, calcium, and sulfur, but it also tends to precipitate any soluble aluminum that may be present in the soil. Limestone is used for neutralizing soil acids, but it usually carries both magnesium and calcium, which may be of importance in the ionic ratios of the soil solution. Sodium chloride is not believed to have any direct value as a plant nutrient, yet it influences the total concentration of the soil solution and has been found effective for increasing crop yields under certain circumstances. A large part of the research in soils has for its purpose the determination of the concentration and reaction of the soil solution; its rate of renewal from the soil; and the influence upon it of applications of manure, liming materials, and fertilizers.

More recently it has come to be recognized that consideration should also be given to the lower horizons of the soil. Here, as in the surface horizon, the conditions as to the reaction of the soil solution, its content of nutrients, and the ratios in which the several ions exist, may not be suitable for the roots of plants. More attention is being given now than formerly to incorporating lime at greater depths in the soil, either by dropping it on the bottom of the plow furrow or by placing it even more deeply by the use of a subsoiler. Also, as the rate of application of fertilizer increases, there is a tendency toward placing part of it down more deeply in the soil, either by plowing it under or by dropping it on the bottom of the furrow. In proportion as conditions at these lower levels become more favorable, plant roots tend to penetrate the soil more deeply, thus tapping additional supplies of nutrients that are naturally present at these lower levels. These deeper roots are much better protected against drought than are those which are largely confined to the plow depth of soil.

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CHAPTER XI

THE CONTROL OF SOIL WATER

One of the most important problems in soil management is that of regulating the water supply within limits that will allow for growing satisfactory yields of crops. In humid regions, special consideration must be given to artificial drainage as a means of control of gravitational water. In arid regions, irrigation is of primary importance. But no matter whether the water has been supplied to the soil by rain or by artificial means, its conservation is essential. In this connection, such practices as cultivation, the accumulation of organic matter, and the choosing of crops adapted to the moisture supply merit special attention. It may also be well to note that irrigation is receiving more consideration each year in humid climates, and that artificial drainage is employed in the control of alkali in the irrigated arid regions of the West.

ARTIFICIAL DRAINAGE IN HUMID REGIONS

It is estimated that over 75 million acres of land in the United States are unfit for cropping until they have been drained. Most of the land now under cultivation is only partially tile drained, if considered from the point of view of producing maximum crop yields. The extent to which artificial drainage is necessary for maximum yields in humid climates is determined chiefly by the topography of the land, the nature of the subsoil, the amount and distribution of the rainfall, and the crops to be grown. With land that is practically level, and under conditions in which the water table tends to remain close to the surface of the soil for considerable periods in the spring or following heavy rainfall, it is quite common to install complete systems of tile drainage with laterals regularly spaced and relatively close together. If the topography is rolling, the main lines of tile usually follow the water courses and the laterals extend out in various directions, depending upon the need for them. Under any conditions, it is highly desirable to make a map of the farm on which the exact positions of the lines of tile are marked. This permits of locating these lines when repairs are necessary or when additional laterals are to be installed.

The nature of the subsoil determines the depth of the lateral lines of tile and the distance between them. It is believed to be good practice to place tile at an average depth of approximately 3 feet unless a very compact layer of soil, commonly called *hardpan*, is found above that depth. In such an event, the tile are usually located at the level of the top of this hardpan layer. If this happens to be relatively near the surface, it is the common practice to supplement the underdrainage with a systematic plan of surface drainage. This usually consists of plowing the field in long narrow lands with finishing furrows between, in which the surface water is collected and carried off into the natural surface-drainage channels.

When the subsoil is such that the lines of tile cannot be placed to advantage at any considerable depth, it may be desirable to change the system of cropping to one in which only those crops are grown that thrive in wet soils. Very wet land is better suited to pastures than to cultivated crops. Such crops as buckwheat, soybeans, oats, alsike clover, and red top will grow fairly satisfactorily on soils that are too wet for corn, sugar beets, tobacco, alfalfa, and most of the market garden crops.

SOME EFFECTS OF ARTIFICIAL DRAINAGE

An excess of water beyond that required to bring the soil to a point approximating two-thirds saturation will have an injurious effect on most crop plants if it is maintained for any considerable length of time. This is due to inadequate aeration of the soil, by reason of which plant roots cannot excrete carbon dioxide, the aerobic bacteria cannot function, and the anaerobic bacteria bring about the reduction of nitrates and of other soil compounds. Another difficulty with a soil containing an excess of water is that its temperature is considerably lower than that of a well-drained soil. This is shown in the accompanying table.

TABLE 52

TEMPERATURES* OF DRAINED AND UNDRAINED SOILS (KING)

Day of Month	Time of Day	Air Temperature	Drained Soil	Undrained Soil
April 24	4 P.M.	60.5	66.5	54.0
April 25	3 P.M.	64.0	70.0	58.0
April 26	2 P.M.	45.0	50.0	44.0
April 27	2 P.M.	53.0	55.0	50.7
April 28	8 P.M.	45.0	47.0	44.5

* In degrees Fahrenheit.

It is particularly desirable that the temperature of the soil be increased as rapidly as possible in the spring for early market garden crops or for such crops as corn which require a long season of warm, growing weather. The water table usually recedes to lower depths as the season advances so that crops like soybeans, which can be sown

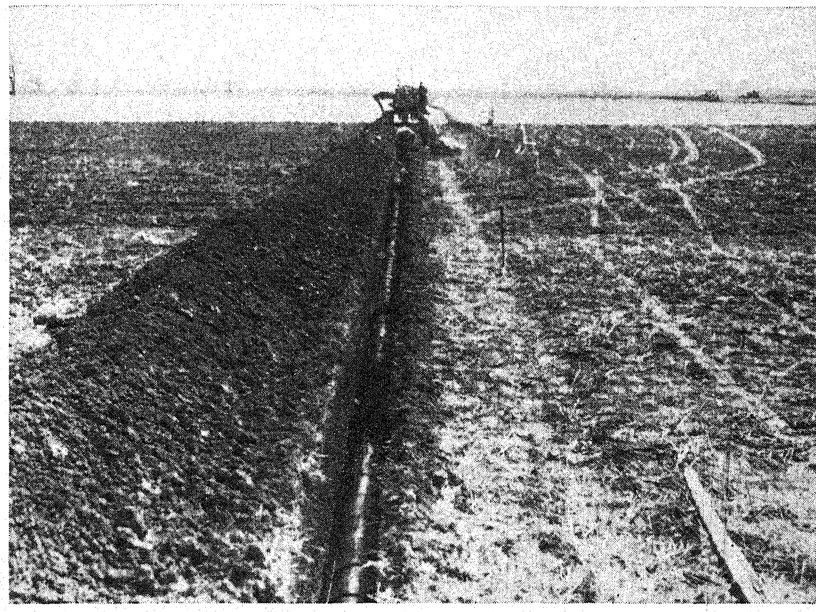

FIG. 16. Tile drainage is particularly effective in level areas of heavy soil. Picture shows a ditching machine in operation.

somewhat later and whose root systems are not so extensive, can be grown on soils that are not sufficiently well drained for corn. The fact that crops differ in their drainage requirements is indicated in the following table, which gives the average of yields of corn, soybeans, wheat, and clover on drained and undrained Clermont silt-loam soil for the twelve-year period in which the experiment has been in progress.

The soil of each of the above plots is slightly ridged in the center so that the water does not stand on the surface of the undrained land. For that reason, the benefits from drainage are not as great as they would otherwise have been. Cool, moist soil meets the requirements of wheat and timothy, but the water must not be in too great excess and the land must be sufficiently rolling to permit of good surface drainage. It is evident that corn is benefited most, while the soybean yields are less on the drained than on the undrained soil. As previously noted, some plants are not injured by concentrations of carbon dioxide that are

TABLE 53

EFFECT OF TILE DRAINAGE ON ACRE YIELDS* ON CLERMONT SILT LOAM (THORNE)

Crops Grown in Rotation	Undrained Land		Drained Land	
	Grain	Stalks	Grain	Stalks
Corn	41.8	19.5	44.5	28.4
Soybeans	16.7	22.2	14.9	17.8
Wheat	20.5	23.0	23.3	24.3
Clover†	....	29.1	....	33.5

* Yields in bushels of grain and hundredweight of stalks and straw.
† Red clover and timothy mixed.

fatal to others. Furthermore, there are differences in the root systems of plants although these are modified somewhat by the conditions of the soil in which they are growing.

Of interest in this connection is the fact that tile drainage reduces the need of acid soils for lime. This is shown in some tests on certain experimental farms in Indiana where comparisons were made of the "lime requirements" of tile-drained and undrained soils by the potassium nitrate method of extraction.

TABLE 54

LIME REQUIREMENTS* OF DRAINED AND UNDRAINED ACID SOILS (CONNER)

Location	Tile-drained	Undrained
Westport	860	1280
North Vernon	1880	2840
Worthington	740	1600

* Expressed as pounds of calcium carbonate required for 2 million pounds of soil.

AVAILABLE WATER IN DRAINED SOILS

For high yields of most crops and particularly for intensive farming, the movement of water through the soil should be so rapid that the water table is lowered below the root zone within twenty-four hours after rain has ceased. If the water table is under control to a depth of 3 feet, so that the roots may penetrate the subsoil without subsequent injury from excess water, the danger from drought is very much reduced. Some idea of the amount of water that may be available for crop use in drained soils is obtained from the following data which were secured by saturating 6-foot columns of soils with water and allowing them to drain for a period of two months. The bottoms of these columns were in contact with a water table.

TABLE 55

PERCENTAGES* OF AVAILABLE WATER IN DRAINED SOILS TO 3-FOOT DEPTH†

	Dunkirk Fine Sand	Wooster Silt Loam	Brookston Clay
Water-retaining capacities	6.5	30.2	30.5
Wilting coefficients	3.5	7.7	17.5
Available water by difference	3.0	22.5	12.8
Available water in acre-inches	1.6	10.5	5.2

* Percentages of dry weights of soils.
† Water table at depth of 6 feet.

The roots of plants may penetrate the soil to considerable depths below the plane at which the tile are placed, during periods of dry weather. However, they are protected from excess water only to the depth of the tile. For that reason, crops like alfalfa may extend their root systems far below the tile in the summer; but when autumn arrives, and the subsoil is filled with water to the level of the tile, the lower portions of these roots die. When freezing and thawing occur in the spring, plants thus injured are subject to heaving.

DRAINAGE WITH IRRIGATION

It is evident that sandy soils are suitable for cropping purposes only in early spring and during rainy seasons, except as the water table is

California Corrugated Culvert Co.

FIG. 17. Portable-pipe irrigating systems provide economical insurance against drought in humid areas.

relatively close to the surface, or under conditions in which supplemental water can be supplied by irrigation. In contrast, a silt-loam soil not only has capacity to store large amounts of water, but the rate of movement of this water to points at which it is being extracted from the soil by roots is quite rapid. By reason of losses of water through transpiration and evaporation, considerable attention has been given to irrigation, even in humid climates, as a means of preventing crop damage from drought and of keeping the crop growing satisfactorily. This is especially important in market gardening, in which succulence and earliness to market are very important. In this case also, the acre values of the crops are sufficiently high to justify the expense of overhead or furrow irrigation.

The ideal arrangement is one in which the water table is kept under control, throughout the season, by drainage and irrigation. This is possible on areas located along bodies of fresh water, into which the excess water may be drained or pumped and from which it may be returned as required. The large areas of swamp land lying around the Great Lakes and other inland bodies of fresh water will probably be utilized in this manner when economic conditions warrant the necessary expenditures to put the system into effect. The overhead system of irrigation is being used in market gardening in humid climates with excellent results. This permits of regulating the supply of water at the optimum required for succulent growth or for fruiting, provided the soil is well drained.

IRRIGATION IN ARID REGIONS

In those regions in which the annual rainfall is less than about 25 inches, it is the practice to apply water regularly by irrigation if there is an adequate supply of water available for this purpose. It is estimated that over 50 million acres of land in the United States will ultimately be under irrigation. The quantities of water to apply and the times and methods of its application are problems which are receiving the attention of experiment station workers in California, Colorado, Idaho, Montana, Utah, Wyoming, Oregon, Texas, Nevada, and New Mexico, in which the major irrigation projects are under way. If the supply of water were unlimited, the aim would ordinarily be to maintain the water content of the soil at the optimum, within economic limits. Usually, more land is available for irrigation than is required to utilize the supply of water. The problem resolves itself into one of deciding between the growing of crops under optimum conditions on a restricted acreage and the utilization of smaller amounts of water over a larger area. It is found that the highest return per acre-inch of water is usually secured when somewhat less than the optimum amount of water is supplied.

Probably the best expression of the relationship between water supply and crop yield, which permits of determining the point at which it becomes advisable to bring more acres of land under irrigation rather than to apply more water to the acreage already being irrigated, is that known as the *evapo-transpiration ratio*. This is the number of pounds of water lost from the soil by evaporation and transpiration for every pound of dry matter produced. In this ratio, consideration is given to the total amount of water added to the soil during the crop season, both by rainfall and irrigation, as well as to the difference in the moisture content of the soil at the time of planting and at harvest. The following table gives these ratios for corn, sugar beets, wheat, alfalfa, and potatoes, as determined in Utah.

TABLE 56

THE EVAPO-TRANSPIRATION RATIOS OF IRRIGATED CROPS (WIDTSOE)

Water Added*	Corn	Beets	Wheat	Alfalfa	Potatoes
10	275	571	948	621	1255
15	356	663	1038	977	1411
20	416	682	1317†	946	1466
30	527	889	1530†	1253	2242
50	1087†	1186	1809	1480	3060‡
Inches Soil Water§	5.54	10.25	13.74	14.91	6.17

* Acre-inches of water added by irrigation.
† Five inches more water added than table indicates.
‡ Five inches less water added than table indicates.
§ Water in soil at beginning of season plus the rainfall.

With wheat, oats, and corn, it is very important that water be applied when the grain is at the " filling out " stage. With sugar beets, potatoes, and carrots, the best results are obtained when water is added throughout July and August, the months of warm sunshine and of best growing weather. Onions and cabbage require a continuously moist soil. It is best to water alfalfa immediately before or after each cutting.

Water may be applied by sub-irrigation, by flooding, or by the use of furrows. The first method is more economical of water but is too expensive. A further objection is that it tends to increase the concentration of alkali salts in the surface soil. A system of flooding is employed for grain crops, while furrowing is the common method of irrigating potatoes and market garden crops. Furrowing is somewhat more economical of water, by reason of the reduction in the loss by evaporation.

THE NET DUTY OF WATER

A term which has come into use in the discussion of irrigation is *net duty of water*. By this is meant the amount of water that is absorbed by the soil for the growth of optimum yields of crops. It does not include the water that is lost by surface run-off nor that which

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FIG. 18. The eroding action of surface run-off is effectively stopped by a permanently sodded draw.

escapes from the irrigation canal or lateral. The net duty of water varies with the climate, the soil, and the crop to be grown. Under given climatic and soil conditions, the net duty of water is highest for rice, with alfalfa, sugar beets, potatoes, corn, and wheat following, in the order in which they are mentioned.

IRRIGATION WITH DRAINAGE

The most effective method of removing alkali salts from irrigated soils is by the use of an excess of water and its removal through tile drains. The problem is quite similar to that involved in the drainage of lands in humid regions except that irrigation water takes the place of rainfall. By reason of the high solubility of alkali salts, they can be readily leached out of the normal soil if it is underlain with tile. If it happens that the alkali contains considerable amounts of sodium and potassium carbonates, the deflocculated condition of the soil may make drainage difficult. Usually the alkali can be readily removed by this process.

In an experimental project in Utah, a 40-acre tract of land was tile drained at a depth of 4 feet, the laterals being placed 150 feet apart. The surface soil was of a silt-loam nature, and was underlain with a somewhat heavier clay-loam subsoil. The following table shows the effectiveness of combined irrigation and drainage by which over 5300 tons of salts were removed in the drainage water. In addition, considerable amounts of the alkali were carried below the depth to which roots ordinarily penetrate the soil.

TABLE 57

REMOVAL OF ALKALI BY IRRIGATION WITH DRAINAGE (DORSEY)

Date of Sampling	Water Added,* Inches	Alkali Salts in Soil in Parts per Million			
		1st Foot	2nd Foot	3rd Foot	4th Foot
Sept., 1902	0	17,038	19,250	22,075	24,775
May, 1903	14	6,238	8,125	13,325	15,813
Oct., 1903	50	1,263	2,288	4,125	7,608
Oct., 1904	47	475	1,600	2,650	6,250

* The water was added in varying amounts from month to month. An additional 13 inches was contributed by rain and snow.

THE CONSERVATION OF SOIL WATER

Whether the soil be watered by irrigation or by rain, it is desirable to conserve the moisture supply. In humid regions, the farmer must always be prepared for periods of drought. This preparation consists in having the soil well underdrained in order to permit of the penetration of the roots to considerable depths; in having the soil well filled with humus materials that increase the storage capacity of the soil for available water; in the elimination of weeds as competitive agents; in the control of unnecessary transpiration of water by a previous growth of cover crops or weeds; and in the preparation of a surface mulch as a means of reducing the loss of water by surface evaporation. The last is especially important on irrigated land, since the concentration of alkali in the surface soil is increased if water is lost by evaporation. Data previously considered present conclusive evidence of the effectiveness of the surface mulch in pot tests under conditions of laboratory control.

Further consideration must now be given to the matter of cultivation in relation to its effectiveness in the conservation of water under field conditions.

CULTIVATION TO CONSERVE WATER IN SEMI-ARID REGIONS

Cultivation previous to seeding the crop or between the rows of an intertilled crop has long been thought to be essential in preventing the excessive loss of water from soils by surface evaporation. The success of dry farming, which is practiced in semi-arid regions, has been assumed to lie in storing the rainfall for a considerable period of months and preventing unnecessary loss by surface evaporation and by transpiration by weeds, until such time as a sufficient amount of water has been accumulated in the soil to grow a satisfactory crop.

Some doubt has been cast on the efficiency of the surface mulch under dry-farming conditions by the publication of the data, given in Table 39, from the Kansas Experiment Station. As was suggested, it seems probable that the surface mulch is less effective in semi-arid regions than in humid regions, by reason of the action of dry winds in the former case. There still remains the need for fallowing and intertilling as a means of preventing surface run-off of water and the growth of weeds which waste water through transpiration.

CULTIVATION TO CONSERVE WATER IN HUMID REGIONS

To apply the Kansas data to the humid regions would be to neglect the differences in the rainfall-evaporation ratios. With a high rate of evaporation, the surface soil becomes dry so rapidly and so completely, following a rain, that nothing may be gained by surface cultivation. In humid regions the rate of evaporation is ordinarily much slower. That the production of a surface mulch for the conservation of water may be important under humid conditions is indicated by a comparative test of cultivation and scraping of the soil at Cornell University, in which moisture determinations, at two-week intervals during the growing season, were made on Dunkirk gravelly loam soil which was planted to various crops. The following data, showing the average moisture content of the soil to a depth of 30 inches during the growing seasons of the several crops, are of interest in this connection.

A study of the data in Table 58 shows some very interesting points. In the case of the fallow ground, there was a very definite moisture conservation in 1925, and an equal loss by cultivation in 1924. The introduction of celery, a crop which has a very restricted root system, resulted in a very positive conservation of water and crop benefit by

TABLE 58

EFFECT OF CULTIVATION ON MOISTURE CONTENT* OF CROPPED SOILS (THOMPSON)

Crop Grown	1921		1922		1923		1924		1925	
	C†	S†	C	S	C	S	C	S	C	S
Beets	9.0	8.3	9.8	11.1	8.2	8.0	12.0	11.2	12.1	10.5
Carrots	8.7	8.2	11.1	11.5	9.0	8.0	13.1	12.3	12.7	11.7
Onions	8.7	8.2	11.2	11.2	9.5	9.4	12.0	11.2	11.9	11.4
Cabbage	10.0	9.6	15.2	14.6	10.5	10.6	11.1	10.3	11.4	10.5
Celery	10.1	8.8	13.5	11.7	10.8	8.6	10.8	8.6	10.4	10.0
Tomatoes	7.9	7.4	14.0	12.9	8.7	9.8	11.7	11.6	15.1	12.9
Fallow	...	...	15.3	14.9	10.3	10.4	11.6	13.2	13.8	12.2
Averages	9.1	8.4	12.9	12.6	9.6	9.3	11.8	11.2	12.5	11.3

* Average moisture content of soils (dry-soil basis) during crop seasons of years indicated.

† C = cultivated once each week during growing season. S = scraped with hoe when weeds appeared.

cultivation every season. Apparently the growing of a crop retards the drying of the surface soil by winds and, in the event that the root system does not extend across the intervening space between the rows, makes it possible to conserve considerable amounts of water by cultivation and the formation of a surface mulch.

Whether or not cultivation will conserve water in a field where crops are growing depends upon the nature of the crop as to its top growth, the extent and distribution of its root system, the conditions as to the humidity of the atmosphere, the velocity of the wind, and the amount of water in the soil. If the rain is followed by clear, hot weather with drying winds and the crop is not well developed, cultivation may be of little value. This is especially true following rains of one-half inch or less, in which case cultivation hastens the loss of water. Of 280 moisture determinations in the foregoing tests, the cultivated soil contained more water than the scraped soil in 188 cases. In this connection it may be well to add that, in such comparisons, the advantage is always with the scraped soil since, no matter how carefully the scraping to kill weeds is done, there is a tendency to produce a light surface mulch.

THE CULTIVATION OF CORN

A number of experiment stations have studied the time, depth, and frequency of cultivation of corn in their effects on yields. In some cases, supplemental studies have been made of the moisture content of the soil, as determined by whether the surface of the soil was scraped with a hoe to free it of weeds or cultivated to various depths for the same purpose. Considered from the point of view of crop yields, little seems to be gained by cultivating corn that cannot be secured by any scheme which will eradicate the weeds. The data given in the accompanying table are of particular interest from the point of view of corn yields in relation to cultivation. As a result of 124 tests, scattered over 28 states and representing a wide variety of conditions as to soil and climate, it was found that the average yields on the uncultivated plots were practically equal to those on the cultivated plots.

TABLE 59

Comparison of Cultivation and Scraping on Corn Yields (Cates)

State	Tests	Yields*
Ohio	10	96
Indiana	9	105
Illinois	8	94
Iowa	7	102
Missouri	3	103
Kentucky	9	91
South Carolina	12	99
Virginia	9	88
New Hampshire	10	112
Average of all tests	124	99
10 plots most benefited by cultivation	...	69
10 plots most injured by cultivation	...	135

* Yields of uncultivated plots as percentages of yields of cultivated plots.

Soil moisture is being very effectually conserved in the Great Plains area by leaving crop residues on the surface of the ground. The net effects of this practice are to increase the soaking in of rainfall greatly and reduce the run-off; to lower the rate of evaporation from the surface soil; and practically to eliminate water and wind erosion. To prepare the soil for crops, use is made of a giant duckfoot cultivator which cuts off the roots of weeds and grass about 5 inches below the surface, without turning up a furrow. Corn and sorghum are planted in the openings that are left by the shank of the duckfoot. Cultivation between the rows is accomplished with the same implement. Wheat is sown with a disc drill. By such methods, nearly twice as much water can be conserved and twice the yield of crops can be produced as by the ordinary plowing and cultivating procedures.

THE SOLUTION OF THE PROBLEM OF CONTROLLING SOIL WATER

Water may operate as a limiting factor in the growth of crop plants either by reason of an excess or of a deficiency. If the soil is too wet, the remedy lies either in some system of artificial drainage or in a choice of crops whose root systems are adapted to such conditions. Most of the cereal and fiber crops do not grow well on wet soils and, if such crops are to be grown, it is not worth while to attempt to compromise with wet soils. Fortunately, ditching machines, by which lines of tile can be placed at any desired depth and with a uniform grade, are now available. Once well buried in the soil, these tile will continue to be effective for many years, assuming reasonable care of the outlets and the replacing of any tile that may accidentally be broken.

Irrigation is an efficient means of increasing the supply of water for crops. The problem here is usually one of securing the largest return for each unit of water rather than the highest yield on each acre. Irrigation is most effective under conditions in which the soil is also tiled, so that occasionally the soil may be washed free of the salts that tend to accumulate if all of the water is lost by evaporation and transpiration. Systematic tile drainage is especially necessary where irrigation is practiced in humid regions, since heavy sprinkling or surface irrigation may occasionally be followed by excessive rainfall.

The conservation of soil water by the surface mulch is of especial importance in humid regions. This is particularly true following a heavy rain if the surface soil is not dried out rapidly by bright sunshine and drying winds. Intertilled crop plants with restricted root systems are benefited by the surface mulch more than are those whose root systems extend across the intervening spaces between the rows. Thus, celery, beets, and onions have been shown to be more favorably influenced by cultivation than are corn, cabbage, carrots, and tomatoes. Little is gained by cultivation following a light rain or during periods of extended drought except as it is necessary for weed control. Cultivation of corn, after it is well started, may result in injury to the root systems and do more harm than good. The best policy for most crops seems to be that of thorough preparation of the seed bed and adequate cultivation during the early period of growth of the crop, after which the stirring of the soil may well be limited largely to that which is required to control the weeds.

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CHAPTER XII

THE MECHANICAL IMPROVEMENT OF SOILS

The manner in which soils are plowed and cultivated determines in large part their productivity. Under skillful management, a soil whose physical characteristics make it difficult to handle may be so improved in its mechanical condition as to permit of the preparation of an excellent seed bed, with good chances for a satisfactory crop yield. The system of plowing and cultivating that will give best results depends upon the predominating sizes and arrangement of the soil particles, the nature of the subsoil, the topographic features of the land, the climatic environment of the soil, and the crops to be grown.

FITTING THE PLOW TO THE SOIL

There is a shape of moldboard, a content of soil water, and a depth of furrow slice that is best suited to improve the tilth of each class of soils. If the soil is of a sandy nature and has a tendency to be too open and porous, it should be plowed deep when it is somewhat wet, with a plow having a steep moldboard. If the soil contains a considerable percentage of silt and is not in good tilth, it should be plowed when it is somewhat dry, and with the use of a moldboard having only a moderate slope. If the soil is a clay and must be plowed when somewhat wet, the moldboard should be relatively flat and the depth of plowing should be shallow. A very dry silt-loam or clay soil will be better pulverized by deep plowing and the use of a steep moldboard. Under such conditions it may be best to disc the surface of the soil before plowing, in order to break up the clods that would otherwise be turned under to a depth that would not allow their being reached by the implements that are used in the preparation of the seed bed.

In manufacturing plows to suit different classes of soil and varying soil conditions, four distinct types have been developed. The sod plow has a long moldboard which slopes gently upward with considerable twist; this prevents the furrow slice from falling back into the furrow and also tends to break the sod apart. The stubble plow is fitted with a moldboard which is quite steep and short and which pulverizes the furrow slice as it turns it over. The breaker-rod and disc types of plows are used in soils that will not scour the moldboard. The disc type is also useful in soils that must be plowed while very dry.

The use of the wrong type of plow may make it almost impossible to prepare a good seed bed. Since most fields contain more than one type of soil and many farmers have only one type of plow, it becomes especially important to learn how to adjust the plow to meet the average requirements of the field. The mechanical improvement of the extreme types of soil in the field must then be effected by subsequent cultivation or by some special treatment designed to meet their needs.

THE DEPTH OF PLOWING

It is believed to be good practice to vary the depth of plowing according to the nature of the soil and the crop to be grown. Clay soils are not usually plowed as deeply as sandy soils. Especially deep plowing is recommended for such crops as alfalfa and potatoes. In most cases, the depth of plowing is determined by the level of productivity of the soil, the amount of organic residues to be incorporated with it, and the quantities of fertilizer and lime to be applied. There is probably little to be gained by deep plowing if by this means the available nitrogen and mineral nutrients of the surface soil are diluted with unproductive sub-

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FIG. 19. Plowing exposes land to the erosive action of wind and water. On rolling land, one answer lies in laying off the cropping areas according to the contour.

soil. The plowed depths of soils usually contain the greater portion of the feeding roots of plants, particularly during the early period of their development. If subsoil is mixed with the surface soil, the unoxidized compounds of the former may exercise a toxic effect on the young seedlings. The "rawness" of the subsoils of semi-arid regions is largely due to a lack of available nitrogen. In humid climates there is the additional factor of toxicity. Traces of compounds containing certain elements in a low state of oxidation, sufficient to be toxic to young plants, would probably not be adequate to cause injury to more mature plants when their roots later penetrate to considerable depths in the subsoil. Furthermore, root-hair development in the subsoil does not take place to any considerable extent except in air spaces in which the soluble soil compounds are probably present in a highly oxidized state. If deep plowing is to be done, it is thought to be good practice to plow as far in advance of planting as may be possible.

TABLE 60

ACRE YIELDS* OF CROPS AS RELATED TO DEPTH OF PLOWING (WILLIAMS)

Crop	Ordinary, 7½ Inches	Double-disc, 15 Inches	Ordinary, with Subsoiling
Corn, bu.	61.1	59.4	61.3
Oats, bu.	49.0	49.2	49.0
Wheat, bu.	31.5	31.4	31.6
Clover, cwt.	53.0	50.6	52.0

* Twelve-year averages on Wooster silt-loam soil.

Loosening the subsoil has usually been attempted either by using a subsoiler, which follows after the ordinary moldboard plow and breaks up the bottom of the furrow, or by the use of a double-disc device that turns two furrows — one following and beneath the other. The former implement is employed to break up the *plow sole* that develops in some types of soil as a result of the compacting action of the plow, the feet of the horses, or the wheels of the tractor, on the bottom of the furrow. The double-disc plow has the further advantage of thorough pulverization of the subsoil and of mixing some of it with the surface soil without depositing the former on the surface, as occurs with ordinary deep plowing. Dynamite has also been tried for breaking up tight clay subsoils in order to facilitate drainage and aeration.

The evidence in favor of these special methods of opening up the subsoil is not conclusive. It indicates that little is to be gained, in extensive farming, by plowing to a depth of more than 6 or 7 inches.

However, it is of interest to note that "backfurrows" are usually more productive than the remainder of the field. It seems probable that, in the more specialized types of farming in which the liming, manuring, and fertilizer treatments are much more liberal, the effects of deep plowing would be greater than they are in general farming. Extensive experiments in very deep plowing are being undertaken on some soils that have been exhausted by centuries of cultivation in Italy. In "coal-stripping" operations it has been shown that the "raw" subsoil, after a few years of exposure, is highly productive of sweet clover. This is followed by a luxuriant growth of bluegrass which is much to be preferred to the pasture vegetation of these same hillsides previous to their being torn up with steam shovels. It is apparent that deep plowing would be especially advantageous with soils having a very sandy *A* horizon, and a much heavier *B* horizon. This would mix clay with the sand.

TABLE 61

ACRE YIELDS* FROM DEEP TILLING, SUBSOILING, AND DYNAMITING COMPARED TO ORDINARY PLOWING (SMITH)

Tillage	Corn, 9 Crops	Soybeans, 7 Crops	Wheat, 6 Crops	Sweet Clover, 6 Crops
Plowed 7 inches deep	40.2	16.3	13.5	3.68
Subsoiled 14 inches deep	41.9	16.2	12.9	3.65
Deep-tilled 14 inches deep	37.4	15.2	10.8	3.18
Dynamited	40.3	16.4	11.7	4.25

*** Bushels of grain and tons of sweet clover per acre on gray silt loam on tight clay.**

TIME AND METHOD OF PLOWING

The date of plowing in preparation for spring and winter crops is a matter of considerable importance in those regions in which the winters are cold and the summers are relatively short. Ordinarily, the problem of distribution of labor makes fall plowing desirable. From the point of view of the effects on crop yields, little is gained by fall plowing which cannot be accomplished by early spring plowing, unless it be the destruction of insects. The undesirable features of fall plowing lie in the failure to take advantage of the opportunity to grow a cover crop, and in the losses that may occur through leaching and erosion. The farther north the land lies, the less these objections apply. On the other hand, it is apparent that, if for any reason spring plowing is delayed, the losses of water by transpiration may be such as to cause a deficiency in the stored supply that will result in reduced crop yields in seasons of scanty rainfall. There would undoubtedly be considerable difference between the water content of soils that are plowed in March and those that are plowed in May, particularly if the field were covered with a rank growth of some green manuring crop such as rye or sweet clover.

The importance of plowing as far as possible in advance of planting the crop is found to be especially great in semi-arid sections where it is necessary to have the soil in condition to absorb the rainfall and to prevent the loss of water through transpiration by weeds. It is quite common, in regions of limited rainfall, and in preparation for such crops as corn, to " list " the soil and to plant the seed in the bottom of the resulting furrows. The lister is a double plow, the shares of which throw the soil in opposite directions, leaving the field in a condition of alternate ridges and furrows. Subsequent cultivation, after the corn is of some height, fills the furrows. Meanwhile the corn roots are protected from drought by the dry layer of soil above.

When plowed soil is subjected to the action of freezing temperatures, it tends subsequently to be easily prepared for the crop. If the plowing is done in the autumn and the winter weather is mild, the good effects of freezing may be entirely overcome, in the case of soils containing considerable silt and clay, by the action of heavy rains which tend to cause the soil to " run together " during periods in which it is thawed. It is because of this that early spring plowing is sometimes better than fall plowing if the work can be done sufficiently early to be assured of several freezing nights. Stiff clay soils, or those that are somewhat wet or difficult to manage, become quite friable under such conditions. Extremely cold winters or hot, dry summers will usually be found to have a marked effect in improving the tilth of soils, probably by reason of the dehydrating effect of these conditions on the colloidal matter in the soil.

In areas of flat land that tend to retain the water, " bedding " the soil may be desirable. In bedding, the field is plowed in relatively narrow parallel lands, with intervening finishing furrows to hold the surface water until it drains away. In hilly regions the two-way plow is used, the furrows following the contour. Here, the soil is sometimes thrown " up hill," so that when it rains the water will run in between the furrow slices rather than over them, and erosion is thus prevented.

Where erosion becomes too serious, either by reason of the steepness of the slope or because of the nature of the soil, some type of terracing is advisable. This may be done either by plowing the soil in small " lands " in which the furrows follow the contour lines or by the use of the *Mangum terrace*. When the Mangum terrace is used, the back-furrows, or ridges made by other means, are made to cross the contour lines at a slope of 6 to 8 inches in 100 feet. The crop is planted or sown in rows, the direction of which, on relatively steep slopes, is the same as that of the terracing ridge. As the water gradually finds its way to this ridge, it is conducted along its upper side to some natural outlet. Large acreages of rolling land in North Carolina, where this scheme of terracing originated, are now being farmed successfully. Considerable attention is also being given to similar types of terracing in other states.

MEANS OF ELIMINATING GULLIES

A large part of the land under cultivation is subject to erosion to such an extent that gullies of greater or less depth have been formed or are likely to be formed after the soil has been put under cultivation. In most cases, it is not feasible to tile rolling land to such an extent that all the water is removed through the tile. The farmer must always be prepared for surface drainage, which in times of storm may reach considerable proportions. Probably the best method of control lies in a combination of a sodded, overflow channel lying along the side of the main line of tile, protected at its lower end by a cement dam and a spillway. It often happens that gullies are formed before such a method of control has been put into operation. Two general methods for their eradication have been found to be effective. One of these is a double V-shaped wire and brush dam. Stakes to which the wire is attached are driven into the ground in such a manner as to put the tip of the V down stream and at such depths as to have the overflow in the center of the dam. As the soil collects back of the dam, weeds and grass begin to grow and the gully fills up.

For larger gullies, the *Adams earth dam,* originated in Missouri, is the most economical and effective scheme yet suggested. This consists in building a dam of soil over the mouth of the gully and conveying the water under the dam through combined vertical and horizontal lines of tile. The vertical tile takes the water from a level somewhat below that of the top of the dam. In a relatively short time, very large gullies may be filled up and farming implements can be taken across without difficulty.

PREPARATION OF THE SEED BED

If the plowing has been well done, the subsequent preparation of the seed bed is usually accomplished without difficulty. This is particularly true where the soil has enjoyed some years of good management in which attention has been given to drainage, the use of lime, and the incorporation of adequate amounts of organic matter with the soil, as well as to good plowing. If such has not been the case and if the weather happens to be unfavorable, the problem of seed-bed preparation may be somewhat difficult. Much depends upon the skill of the farmer and his experience with similar soils and conditions.

In preparing the plowed soil for seed or plants, it is desirable that the surface soil be made fine and free from clods, while the subsurface must be compact and also without clods. The first is essential in order to get the seed or plant roots adequately covered, and the second to provide for a continuous flow of capillary water from the subsoil. For these reasons, it seems desirable to make use of implements that will effect both the pulverizing and the compacting of the soil. The disc, the spring-tooth harrow, and the smoothing harrow are commonly used for pulverizing the surface soil, the choice depending upon the nature of the soil, the crop residues contained in it, and the recentness of plowing. The smoothing harrow has its chief value on soils that are in good tilth, where it can be used for leveling the surface, forming a surface mulch, and killing weeds. The spring-tooth harrow is especially useful for deeper cultivation on soils that contain very little coarse organic material that would be dragged to the surface. The disc is an efficient tool for cutting up sods and other coarse organic materials, such as weeds, corn stover, and green manuring crops. It can also be used as a substitute for the plow under conditions in which the crop residues on the surface of the soil are somewhat limited.

In compacting the soil, use is made of the drag, the roller, and various types of combined rollers and cultivators, of which the cultipacker is an excellent type. The drag is used primarily as a leveling agent. The roller compacts the subsurface and increases the rate of flow of water from the subsoil up to the planted seeds. The better growth of grass in the footprints on a newly seeded lawn and the earlier germination of seeds that have had the soil compacted over them by the planter wheel are evidence of this increased supply of water. The objection to the roller lies in the fact that the clods are often simply pressed into the soil and are not pulverized. Furthermore, the roller leaves the surface of the soil smooth and compact, and tends to hasten the loss of water by evaporation. The cultipacker combines the desirable features of the roller and the smoothing harrow, and in addition is very effective in pulverizing clods.

THE CONTROL OF CLODS

If, by reason of necessity, certain soils are plowed when too wet or too dry, the resulting clods are very difficult to pulverize. The remedy may be said to be in managing the soil in such a way as to prevent the formation of clods. The use of lime on acid soils or on those containing considerable amounts of colloidal matter has a very noticeable effect in improving their tilth. Incorporating coarse organic matter with the soil tends to form lines of weakness in the soil masses that prevent the formation of large clods. The growing of plants with extensive or fibrous root systems, which on decaying leave pores through the soil, is an effective method of preventing clods. Sweet clover has been recommended for such purposes. Cornstalks and similar coarse organic materials may serve a useful purpose on heavy soils. Tile drainage permits the removal of very finely divided colloidal material from the soil, the opening up of pore spaces, and the better development of root systems.

If a soil tends to be cloddy, it is desirable to keep livestock off the fields while the soil is wet, particularly in the spring of the year preceding plowing. Once clods have been formed, the only method of attack lies in the use of some implement such as the cultipacker. If the clods are frozen or are thoroughly dried out and subsequently moistened by the rain, they can easily be pulverized. It is well to remember that sandy soils, in contrast to silt loams and heavy clays, can be improved physically by being plowed and cultivated while they are wet.

EFFECT OF CHEMICAL AGENTS ON SOIL STRUCTURE

Mention has been made of the effect of lime in improving the structure of clay soils. This improvement is the result of the direct effect of lime in flocculating the colloidal particles, and of its indirect effect in stimulating microbiological activities, as a consequence of which the binding effects of the resulting humus are brought into play. Flocculation is usually the first step in the formation of *soil aggregates*. Salts vary greatly in their effects on flocculation. Divalent cations, such as calcium and magnesium, have flocculating effects even when applied as carbonates and hydrates. On the other hand, the carbonates and hydroxides of ammonium, potassium, and sodium are very active deflocculating agents. Sulfate of ammonia and other acid-producing salts, most neutral salts, and all acids are active flocculating agents. The cations of these salts and acids effect a neutralization of the negative charge associated with the colloidal particles and cause their precipitation. Alkali soils, notwithstanding their alkalinity, possess definite structure because of their high content of salts. Gypsum is of particular interest as a flocculating agent by reason of its wide distribution as an industrial by-product and in nature. It is low in cost, has relatively high solubility, and can be used to advantage as a supplement to limestone for supplying calcium to the lower soil horizons.

Where sodium nitrate is used in liberal amounts each year, it is probable, if the soils contain very much clay, that objectionable deflocculation effects will be noted after a time. This is quite likely to occur under apple trees to which applications of nitrate of soda are regularly made. Since sulfate of ammonia has the opposite tendency, both as to its effect on the consistency of the soil and on the reaction, it seems quite logical to use these two materials in alternate years so that the effects of the one are overcome by the other.

The amount of a flocculating reagent that is required to produce the desired results depends upon the reaction of the soil. Bradfield has shown that about ten times as much cation is required to flocculate a soil having a pH of 9 as one having a pH of 5.

THE SOIL IN RELATION TO FLOCCULATING AGENTS

In contrast with clay, sand may have its consistency improved by the use of deflocculating agents. Materials like nitrate of soda and wood ashes are useful in this connection. Heavy applications of well-rotted manure are valuable for increasing the content of organic colloids in sands. Gardeners use large amounts of manure with good effect, but most market gardening is done on sandy-loam soils. Repeated heavy dressings of manure have been known to injure the physical qualities of clay soils, probably by reason of the resulting excess of colloidal materials. Soils that are constituted mainly of very fine sand and silt cannot be improved in structure by chemical agents, since particles of these sizes do not flocculate.

Of particular interest is the fact that acid soils tend to become deflocculated and to lose both their organic and inorganic colloids by leaching, as a result of which these colloids are carried to lower depths. They tend to clog up the pores of the zone of accumulation in the subsoil and produce a hardpan layer. Limestone boulders accidentally buried in acid subsoils, when later excavated, have been found to be covered with a black layer of calcium humate resulting from the precipitation of these organic colloidal materials.

EFFECT OF PLANT ROOTS ON SOIL STRUCTURE

Certain crops have been found to produce very marked effects on soils of poor consistency. Rye, buckwheat, and timothy may be mentioned in this connection. The explanation apparently lies in their very fibrous root systems. These are so well spread through the soil as to produce lines of weakness which prevent the formation of clods when the soil is subsequently plowed. All of these crops are credited with exhausting the soil. They seem to be able to grow satisfactorily on soils that are both acid and deficient in mineral nutrients. If the latter condition is recognized and fertilizers are applied to the succeeding crop, the combination of good mechanical condition and adequate supplies of the nutrient elements is conducive to satisfactory yields on soils that otherwise would not be productive.

Sweet clover, alfalfa, and other crops that produce long tap roots are believed to be useful in opening up channels through very heavy subsoils. The openings through the subsoil that were left by the roots of the original forest trees were filled with soil after the land was put under cultivation. It seems probable that a reopening of similar channels would serve a useful purpose in effecting more adequate drainage and aeration. If this can be accomplished by the above crops or by any others that are yet to be experimented with, it seems worth while to give them a trial.

THE CULTIVATION OF CROPS

Much of the necessary cultivation of crops can be done before planting takes place. If the seed bed is thoroughly prepared, it will be free of clods; the subsurface will be compact; and the surface soil will be fine and loose. As soon as the field is planted to any intertilled spring crop, the process of eliminating weeds as crop competitors can begin. The use of some type of weeder, or even of a smoothing harrow, in a field that is planted to such a crop as corn, will meet all of the requirements, both for the purpose of a surface mulch and for weed control, until the plants are so large that some type of row cultivator must be employed. From that time forward, cultivation for the purpose of destroying weeds is of primary importance, the depth being limited to that which loosens enough soil to cover those that are in the row.

If no weeds are present, the need of cultivation for moisture conservation in humid climates decreases with the development of the crop, until the time arrives when the root systems of most crops are so well distributed that little water escapes them. In practice, the logical thing to do is to begin with fairly deep cultivation while the plants are young and before their root systems are extended laterally, and then to reduce the depth with each successive cultivation. By this means, weeds can be eradicated and the roots of plants are not seriously disturbed. An excessive number of cultivations, beyond that required to control weeds, has not been shown to be of any value to the crop.

TILLAGE AND SOD CULTURE IN ORCHARDS

The relative merit of tillage and *sod-culture* for fruit trees has received considerable attention within recent years. Ordinarily, the process employed has been that of plowing the field before planting the trees, and then continuing to cultivate between the rows until the trees were well established and the space between them was reduced to such a point that intertillage was difficult. From this time on, the natural sod was allowed to establish itself under the trees and cultivation ceased.

If the soil was in a high state of productivity when planting occurred, and if the clean cultivation of each spring was followed by the growing of cover crops which were subsequently plowed under, the clean cultivation system followed by sod was found to be satisfactory. If the soil was relatively unproductive, if during the period of clean cultivation crops were grown and harvested without adequate attention to the use of fertilizer and manure, and if when sod was established it was kept closely grazed by livestock, then the yield of fruit was not satisfactory. Later it was shown that the sod-culture system reduces the supply of available nitrogen to such a point that the lack of this element becomes the limiting factor.

It is now believed that spring cultivation is to be preferred when the land is level because, by this process, nitrates accumulate and the soil continues to yield up considerable quantities of available nitrogen for the trees for some weeks. This is then followed by cover crops, preferably legumes, which are plowed under the following spring. If the land is rolling, the sod is allowed to grow after the trees have become well established, and extra fertilizer or manure is substituted for cultivation.

SHELTERBELT PLANTING FOR WIND-EROSION CONTROL

Dust storms of recent years have focused attention on the necessity of developing improved means of preventing wind erosion of plowed soil. In many cases, particularly with sandy soils, the only feasible means of holding the soil in place is by covering it permanently with grass. Where such land must be kept under cultivation, the use of *shelterbelt plantings* has proved quite satisfactory for control purposes. These plantings are usually from one to three rows of mulberry or cottonwood trees, arranged in an east-west direction, and at right angles to the prevailing winds. A considerable variety of other trees and shrubs are also employed for this purpose. The land is broken up into long, narrow fields, each 10 to 40 acres, somewhat like those used in strip cropping. In some places, all four sides of the fields are enclosed by these plantings.

RÉSUMÉ CONCERNING THE MECHANICAL IMPROVEMENT OF SOILS

Low crop yields are often the result of failure on the part of the man who farms the land to give adequate consideration to the mechanical phases of the problem of soil improvement. The time and manner of plowing, the preparation of the seed bed, the subsequent intertillage of the crop, the prevention of erosion, and the overcoming of errors in previous handling of the soil are all matters that merit serious consideration. Gardeners have longed believed in the old axiom that proper "tillage is manure." That adage originated in the days of Jethro Tull, whose book, "Horse Hoeing Husbandry," written in 1733, is a classic in agricultural literature. It is now known that Tull's belief that plants "insume" the very fine particles of soil was erroneous, and that they use only those substances that are dissolved in the soil water. Nevertheless, as farming becomes more intensified, much more attention is paid to fitting the plow to the soil, to plowing each class of soil according to its needs, and to giving it such supplemental cultivations as the conditions demand.

One of the most important problems involved in the management of soils is that of preventing erosion and of making amends for errors in this connection that may already have occurred. Much can be done in a lifetime to fill open ditches and even to level fields by taking advantage of the carrying power of water and causing it to place its load of soil where it is needed. Badly eroded land may thus be reclaimed for cultivation. It has also been shown that satisfactory orchards can be grown on sod land, where this is required by reason of the steepness of the slope, if nitrogenous fertilizers or manure are substituted for the usual clean-cultivation and cover-crop system that is popular on level lands.

Certain chemical agents and manure may be used to good effect, the choice depending upon the nature of the soil. Of these, the various forms of lime are particularly useful. Heavy applications both of nitrate of soda and of well-rotted manure may be objectionable on clay soils, but are very desirable on sands.

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CHAPTER XIII

SUPPLYING ORGANIC MATTER

Plant residues are a very essential part of most productive soils. They contain elements, essential to the growth of succeeding crops, that are liberated in their decay. They serve as sources of food for energy and growth of soil bacteria. Their carbon, nitrogen, sulfur, and phosphorus, when oxidized and dissolved in the soil water, increase the solvent action on the still undecomposed portions of the soil minerals. The tilth of soils and their capacities to store available water are determined in large part by the quantity and nature of the organic matter contained in them. In general, it may be said that soils are in best condition to produce satisfactory yields of crops when they are well supplied with partially decomposed plant and animal residues.

THE ORGANIC-MATTER CONTENT OF SOILS

The determination of the quantity of organic matter in soils is somewhat difficult. Estimates based on "loss on ignition" are not satisfactory since, by heating the soil to a low red heat, water and other volatile substances are also driven off and any ferrous iron will be changed to the ferric state. While it is not possible to separate the organic matter as such from the soil, methods have been devised for the extraction of what has been termed humus. Investigation has shown that if a soil is first washed with weak hydrochloric acid, the humus can be extracted from it by treatment with dilute ammonia water. The effect of the acid is to separate from the humus the calcium and other base-forming elements with which it forms insoluble humates, with the result that the humic acids are released. These give a brown to black color to a solution of ammonium hydroxide. Acid soils yield a colored extract with ammonia water without previous treatment with the hydrochloric acid, the depth of color being an index to the degree of acidity.

Humus is soil organic matter that has undergone decay to the extent that it has lost its identity. Examination shows that it contains, on the average, about 58 per cent by weight of the element carbon. The factor 1.724, therefore, is often employed in estimating the quantity of organic matter in soils from the amount of carbon contained in them.

This is on the assumption that the percentage of carbon in the total organic matter in soils is the same as has been found to be the case with humus. In estimating the quantity of organic matter by this method, use is made of the ordinary combustion furnace commonly employed in the ultimate analysis of organic materials. The carbon dioxide resulting from the oxidation of the organic matter of the sample of soil is absorbed and weighed in bulbs containing granular soda-lime. From the total carbon, that which is in the form of carbonates must be subtracted in order to determine the amount that is present as organic matter. In most soils the carbonate carbon is only a very small part of the total carbon.

It has been found that a fairly constant ratio exists between the quantities of nitrogen and of carbon in soils. This ratio, in humid climates, averages a little over 1 to 10. In semi-arid climates it is somewhat higher, although the ratio seldom exceeds 1 to 14. Since nitrogen determinations are somewhat easier to make than are those of carbon, the amount of organic matter is ordinarily roughly estimated by multiplying the nitrogen content by 20. A soil containing 3500 pounds of nitrogen per acre to plow depth has in it about 35,000 pounds of organic carbon and approximately 70,000 pounds of organic matter.

THE QUALITY OF SOIL ORGANIC MATTER

The determination of the total amount of organic matter in the soil may be of little value unless something is known concerning the cropping system that is being employed, and the probable source and age of the organic residues that are present. It is a well-known fact that peat soils containing as much as 80 per cent of organic matter are often very unproductive even when thoroughly drained. Such soils are very high in their content of nitrogen, yet nitrogenous fertilizers are often found to be essential on them for satisfactory yields of crops.

Considered from the point of view of its value as a source of nitrogen for crop use, the quality of the organic matter of soils may be said to be directly related to the recentness of its origin and the quantity of nitrogen that it contains. Well-rotted manure, clover sods, and the early growth of rye are much more useful to crops as sources of nitrogen than are peat, strawy manure, timothy sods, and full-grown rye. The larger the proportion of carbohydrate substances in the organic matter, the smaller the amount of available nitrogen that remains for crop use after the bacteria of decomposition have had their requirements satisfied. Unless organic materials contain $1\frac{1}{2}$ per cent or more of nitrogen, they will yield up little or none of this element for the crop of the season during which they are plowed under or worked into the soil. To overcome such difficulties, straw and similar low-nitrogen materials that are available for use should either be composted, plowed under in conjunction with clover or well-rotted manure, or supplemented with a nitrogenous fertilizer.

Fig. 20. Soybeans, plus the weeds that grow up among them, provide an excellent supply of high-nitrogen organic matter for plowing-under purposes.

Similarly, the quality of organic matter may be considered from the point of view of its content of phosphorus, potassium, and other essential mineral nutrients. The amounts of these elements that are available for crop use in soils are determined in large part by the quantities of them that are contained in the soil organic matter. If one plows under cornstalks and wheat straw and sells the grain in which the phosphorus is concentrated, it is safe to assume that the lack of available phosphorus will soon become a limiting factor in crop growth since the bacteria of decomposition undoubtedly compete with the crop for this element just as they do for nitrogen when the quantity is limited. Muck soils are notably deficient in potassium, although the plant residues of which they are largely composed must have contained large amounts of this element. In this case the potassium has been removed by leaching.

ORGANIC MATTER IN RELATION TO NITROGEN FIXATION

Quality of organic matter, when considered from the point of view of the crop, may not be the same as that which is involved in connection with the process of nitrogen fixation. It has been repeatedly shown that such carbohydrate substances as mannite, lactose, and sucrose are important aids in increasing the rate of fixation of atmospheric nitrogen by azotobacter. The assumption is that the starch, cellulose, and similar organic compounds contained in the fresh residues of plants satisfy the energy requirements of these bacteria in the soil. It is believed that a large percentage of the different species of soil bacteria have the capacity to utilize atmospheric nitrogen under conditions in which the soil contains little or no nitrate. If this is true, then highly carbonaceous materials have a value in the soil at times when no crop is being grown. This would suggest the plowing under of straw and timothy sods as early as possible in the season in order that decomposition processes may be carried toward completion before the crop of the following summer has been planted. Meanwhile, supplemental nitrogen may be accumulated from the atmosphere.

PHYSICAL EFFECTS OF SOIL ORGANIC MATTER

The tilth of soils and their capacities to retain available water are very much improved by increasing the amount of organic matter in them. This organic matter serves as an effective granulating agent in clay soils. In sandy soils it partially replaces clay as a binding agent. In soils that tend to be cloddy, it forms lines of weakness in the masses of particles. With further increase in their organic-matter content, a point is finally reached at which sands and stiff clay soils lose their distinctive characteristics. A comparison of the soil of the garden, which is usually very heavily manured every year, with that of the nearby fields, on which the quantity of manure that is applied is too small to be of any particular importance as a direct source of organic matter, makes this evident.

The significance of the organic matter in improving the physical properties of soils is apparent, if one considers the characteristics of muck and peat. These materials are able to absorb water to the extent of attaining from two to three times their original weight. At the same time, their volume is very markedly increased. They have a high porosity and are easily drained. They lack cohesiveness and have a low specific gravity, which makes them easy to work. They have a high specific heat and, therefore, are not subject to extremes in temperature. In general, mucks and peats possess the physical qualities that are complementary to those of other extreme classes of soils. While the organic matter of ordinary soils is not necessarily the same as that of peat, some of the effects observed from liberal manurial treatments are quite similar to those secured from mixing peat with other classes of soils.

CHEMICAL EFFECTS OF SOIL ORGANIC MATTER

Most of the nitrogen and a large part of the mineral elements that are used by plants are contained in the soil in the residues of previous plants. These are liberated for crop use during the process of decay. Of these elements, carbon, nitrogen, sulfur, and phosphorus, present largely in organic combinations, are oxidized to their respective acids, which act on the soil complex to liberate its base-forming elements. Additional amounts of the first three of these elements are contributed by the atmosphere. It is because of the dissolving action of water containing these acids that the soils of humid climates ultimately become acid in reaction as the soluble salts thus formed are leached away.

While organic matter, through its decay, hastens the rate of decomposition of the soil minerals, it also serves, when in the form of humus, to adsorb considerable amounts of certain of these elements, and thereby prevents their loss in the drainage water. Soils containing large quantities of organic matter are usually more productive than are those that are deficient in it. The soil humus has somewhat the same characteristics as colloidal clay in that it has a high adsorptive capacity for such ions as NH_4, K, PO_4, and Ca, and also exerts a " buffer " effect which aids in keeping the soil reaction under control. Excessive applications of fertilizers or of liming materials are much less injurious in their effects if the soil contains large amounts of well-decomposed organic matter.

MEANS OF ACCUMULATING ORGANIC MATTER IN SOILS

The gradual reduction in the content of organic matter in soils, as they become farther removed from the virgin state, is evidenced in their poorer tilth and in their lower productivity. In order to restore these properties, farmers have found it desirable to adopt schemes of crop rotation designed to supply more crop residues, to make use of manure and fertilizers as a means of increasing the yield of crops and incidentally of enlarging their contribution to the supply of organic matter, and to grow green-manure crops to be incorporated with the soil.

It is evident that the continuous growth of a clean-culture crop, such as corn, is more destructive of soil organic matter than is the growing of corn in rotation with wheat and clover. If a variety of crops is grown and the proportion of clean-culture crops is not too large, the organic-matter content of the soil can be maintained at a high level by the supplemental use of purely inorganic fertilizers. These make their contribution entirely through the additional amounts of organic residues that remain after the resulting larger crops have been harvested. This is well demonstrated in the following data, which show the relation between crop yields and organic-matter content of soils at the end of a fifteen-year period of experimentation with manures, fertilizer, and lime, on Dekalb silt-loam soil. Of the crops produced during this period, four were clean-culture crops, five were small grains, and the remainder were hay crops. All the crops were harvested and removed, only the normal residues being contributed to the organic-matter supply.

TABLE 62

EFFECT OF FERTILIZERS ON ACCUMULATION OF ORGANIC MATTER (BEAR)

Treatment of Soils	Fertilizers Applied in 15 Years, Tons per Acre	Total Produce in 15 Years, Pounds per Acre	Organic Matter in Soil at End, Pounds per Acre
No fertilizer	None	40,960	42,800
Complete fertilizer	5	117,910	60,800
Manure	190	139,670	73,600
Complete fertilizer and lime	7½*	120,605	49,000
Manure and lime	212½	152,400	65,000

* Two and one-half tons of burned lime.

The use of 5 tons of complete fertilizer during the fifteen-year period resulted in an increase of over 40 per cent in the content of organic matter in the plowed acre of soil. Manure made an additional contribution, but not as much as would be anticipated from the quantity that was applied. Lime evidently increased the rate of decomposition of the organic matter and thereby reduced its rate of accumulation. The evidence is to the effect that soil organic matter is largely a by-product of good farming. The larger the crop, the more refuse available for plowing under. Assuming that the rotation includes sod crops, the supply of organic matter in the soil can be maintained at a high level by the use of inorganic fertilizers alone. In proportion as the soil is kept under clean cultivation, other sources of organic matter must be found. For that reason, market gardeners find it necessary to make use of large applications of manure or to plow under heavy growths of green-manure crops. In the latter case, fertilizers are used to increase the yield of the green-manure crops, not only that more material may be available for plowing under but that it may be richer in the essential nutrients required by the following crop.

MANURE AS A SOURCE OF ORGANIC MATTER

Well-rotted manure is probably the most valuable type of organic matter than can be added to a soil. It combines a number of desirable qualities in that it is fairly concentrated in its nitrogen and mineral constituents; it carries a very active bacterial flora; and the preliminary stages in its decomposition have already taken place before it is incorporated with the soil. If it can be supplied at a rate of from 20 to 40 tons an acre, as is desirable in market gardening, no supplemental green-manuring program is necessary. In extensive systems of farming, the supply of manure is too limited, as a rule, to permit of its meeting the organic-matter requirements of the soil. A 12-ton application of manure every three years to each acre of land in rotated crops is considerably more than the average farmer can make. Yet at such a liberal rate of application, the annual contribution to the soil organic matter would be only 1 ton an acre, since manure is about three-fourths water. On this basis, it would require over half a century to double the organic-matter content of the soil, assuming that none of that added in the form of manure was used up meanwhile. Evidently, if any important increase in the supply of organic carbon in the soil is to be effected in general farming, it must be secured from the atmosphere. This requires that larger yields of crops be produced. Either fertilizer or manure can be used for this purpose. Ordinarily, it is a combination of both fertilizer and manure, coupled with the use of a rotation that takes advantage of the well-known function of legumes, that best meets the requirements on the general farm.

GREEN MANURES AS SOURCES OF ORGANIC MATTER

If green manures are to be employed for improving the soil, it is desirable that they be plowed under in the immature stage rather than later. This is because of the fact that, as maturity approaches, the percentage of carbohydrate substances increases, while that of nitrogen and of each of the mineral constituents decreases. When well-matured rye is plowed under, the bacteria that bring about its decomposition apparently compete with the following crop for these essential nutrients, to the end that the yield is reduced. This is indicated in the following data from a pot experiment in which the various green manures were incorporated with a Dunkirk silty clay-loam soil at different stages of their growth, and studies were made of the rates of accumulation of humus and nitrates and of the yield of the following crop.

TABLE 63

EFFECTIVENESS OF GREEN MANURES AS RELATED TO THEIR MATURITY (MARTIN)

Green Manure Used	Height of Plants, Inches	Dry Matter Added, Grams	Humus* Produced, Grams	Nitrates* Accumulated, p.p.m.	Wheat Yield, Grams
Rye	24	36	556	137	23.4
Rye	48	78	648	114	13.2
Rye	48	150	1215	3	9.4
Oats	11	34	689	225	19.0
Oats	30	63	1008	132	8.5
Oats	36	122	1706	102	4.8
Buckwheat	10	27	879	352	20.2
Buckwheat	20	69	1359	498	13.1
Buckwheat	26	100	1578	416	12.9

* At end of 5-month period.

The efficiency of green manures is, within limits, inversely proportional to their maturity, in so far as the yield of the following crop is concerned. The contribution to the organic-matter content of the soil, at least temporarily, is greatest when the green-manure crop is permitted to grow to maturity. The choice, therefore, will depend somewhat upon the length of time that is to elapse between the plowing under of the green manure and the planting of the following crop. It will be recalled that the carbon-nitrogen ratio in soils is approximately 10 to 1. Any extra carbon, above the amount required for this ratio, will ultimately be lost as carbon dioxide. Its oxidation, however, provides energy for the bacteria that effect its decomposition.

LEGUMES AS GREEN MANURES

Legumes are commonly chosen for green-manuring purposes in preference to other crops, because they contain high percentages of phosphorus, potassium, calcium, and other mineral elements, and because their associated nodule bacteria fix additional amounts of atmospheric nitrogen. Under conditions in which there is a deficiency in any quality of a soil that can be improved by green manuring, the legume type is likely to be most effective. Some of the possibilities of soil improvement by this means are demonstrated in Table 64. In this test, clover was sown in the small grains, and the resulting growth was plowed under the next spring in preparation for the seeding of oats, which was subsequently followed by corn and potatoes.

TABLE 64

Effect of Clover As a Green-manure Crop on Yield of Subsequent Crops (Saunders)

Previous Crop	Oats, Bushels	Fodder Corn, Tons	Potatoes, Bushels
Wheat — no clover	63.5	16.4	353
Wheat — clover	72.9	22.8	396
Barley — no clover	61.1	17.3	346
Barley — clover	70.5	23.6	386
Oats — no clover	58.8	15.0	358
Oats — clover	70.5	20.4	392

Among the more important legume cover crops are crimson clover, cowpeas, and velvet beans for southern latitudes, and soybeans, vetch, and sweet clover for those farther north. The last-named crop has come into prominence in recent years by reason of its very rapid rate of growth and its very remarkable capacity to accumulate nitrogen. It can be sown in the spring with small grains and provides a green manure for plowing under the following spring. It may also be seeded in July in a clean-culture crop for winter cover purposes. The following data on the height, weight, and nitrogen content of sweet clover, at dates when it was plowed under in preparation for the corn crop in various localities in Illinois, are of interest in this connection.

TABLE 65

Acre Yields and Nitrogen Content of Sweet Clover (Whiting)

Field Location	Date of Sampling	Height, Inches	Green Weight, Tons	Nitrogen, Pounds
Urbana	May 2	13	5.8	98
Minonk	April 26	12	9.1	164
Joliet	April 29	9	7.9	133
Toledo	May 9	26	12.8	196
Newton	May 10	22	12.6	188
Rawleigh	May 1	19	12.7	129
Enfield	May 1	18	8.7	124

As a result of plowing under this fresh leguminous material, it was found that an abundance of nitrate nitrogen was present in the soil during the growth of the following corn crop. That considerable amounts of phosphorus, potassium, and other essential mineral elements were supplied to the corn by the decaying sweet clover is indicated in the following table, which gives the weights of roots and tops of an acre of sweet clover at the time of plowing under, May 10, and the quantities of the various essential elements that were contained in them. For comparison, the requirements of a 100-bushel corn crop and a 50-bushel wheat crop are also included in the table.

TABLE 66

POUNDS OF PLANT NUTRIENTS IN AN ACRE OF SWEET CLOVER* (WHITING)

Elements	2600 Pounds Tops	3100 Pounds Roots	5700 Pounds Total	Elements Required by	
				100 Bu. Corn	50 Bu. Wheat
Nitrogen	108.7	110.7	219.4	150.0	96.0
Phosphorus	7.3	5.7	13.0	23.0	16.0
Sulfur	13.3	13.2	26.5	15.3	11.8
Potassium	36.0	17.8	53.8	71.0	58.0
Calcium	40.4	14.4	54.8	22.0	11.0
Magnesium	12.3	12.2	24.5	17.0	8.0

* Crop harvested May 10.

NITROGEN AND MINERAL CONTENT OF LEGUME RESIDUES

Ordinarily, only the residues of crops, rather than the whole plant, are incorporated with the soil. It is of interest, therefore, to consider the relative amounts of the more important plant nutrients in the stubble and roots of the various legume plants. The data in Table 67

TABLE 67

POUNDS OF FERTILIZER NUTRIENTS IN ONE ACRE OF LEGUMES (WOODS)

Crop as Hay	Yield, Cwt.	Nitrogen		Phosphoric Acid		Potash	
		Tops	Roots*	Tops	Roots*	Tops	Roots*
Cowpea	36	95	22	20	6	68	13
Soybean	42	75	13	21	5	73	14
Soybean†	50	165	9	42	2	109	6
Horsebean†	58	171	32	30	6	153	20
Vetch	48	153	27	37	7	163	22
Clover (red)	50	138	44	32	13	152	32
Lupine	46	116	12	26	4	136	17

* Roots and stubble. † Seed partially developed.

show the contents of nitrogen, phosphoric acid, and potash, both in the tops and in the roots and stubble, of a number of legume hay crops. The data indicate that the residues of red clover are much more valuable as agents to effect an improvement in the crop-producing power of the soil than are those of such legumes as cowpeas and soybeans. The good effects of clover, sweet clover, and alfalfa residues must be credited largely to their content of nitrogen, but they make important contributions to the available phosphoric acid and potash content of the soil as well.

OTHER SOURCES OF SOIL ORGANIC MATTER

The most important contributions to the supply of organic matter in soils are ordinarily the roots, stubble, and second growth of the hay crops, which have an important place in the rotation for that reason. Such crops as timothy supply large amounts of organic matter, but this, unfortunately, is usually quite low in its content of nitrogen. Other very important sources of organic matter are the weeds that are normally produced where the hay crop fails, or following the harvesting of the small grains. A heavy crop of ragweeds (*Ambrosia*) is of considerable value in that it contributes not only organic matter but plant nutrients as well. The pigweed (*Amaranthus*) is reported to contain large amounts of nitrate nitrogen. This probably accounts for the luxuriant crop growth that usually follows the plowing under of these weeds. Analyses of weeds show that many of them are very high in their contents of the nutrient elements. Since weeds are usually very good foragers, it is possible that more advantage could be taken of them as catch crops, if precautions were taken to prevent their going to seed. While weeds are usually abundant even though they are kept under control, it seems probable that some of the more luxuriant controllable types might be grown to advantage as a source of seed for catch crop purposes.

THE SOIL IN RELATION TO ORGANIC-MATTER NEEDS

Sandy soils are very much improved by incorporating large amounts of well-decomposed organic matter with them. Organic colloids serve as binding agents and improve the water-holding capacities of such soils. They are effectual substitutes for clay, which accomplishes the same purpose if it is kept in a deflocculated state by plowing the soil wet and by treatment with heavy applications of such materials as nitrate of soda. For this reason, market gardeners attempt to secure and use very large amounts of manure because the soils with which they are dealing are usually sandy loams and respond exceptionally well to such treatment.

On the other hand, heavy clay soils, already containing large amounts of colloidal material, are not improved by the use of such large quantities of well-rotted manure. In fact, it has been found that such soils may best be improved by plowing under such materials as corn and tobacco stalks, strawy manure, and other coarse materials which serve to increase their rate of drainage and permit more rapid drying of the soil and a better aggregation of the clay particles.

For clay soils and for those that are made up largely of non-aggregating particles of very fine sand and silt, fertilizers may be more effective agents in improving the physical qualities than are excessive applications of well-rotted manure. This is because, by stimulating the growth of larger crops with their accompanying larger root systems, the soil is permeated with these roots which serve as lines of weakness in the soil mass and permit of better mechanical preparation of the seed bed. Clods do not form in soils that are filled with fine roots. This is the explanation of the improvement in the physical condition of soils that is often noted following the growth of rye or timothy.

OTHER ORGANIC-MATTER RELATIONSHIPS

It is generally stated that organic matter is of no value directly as a plant nutrient, but that it must undergo decomposition and oxidation to be useful to plants. It has been shown, however, that plants are able to utilize a considerable variety of organic nitrogen compounds, such as acid amides and amino acids. In fact, there is reason to believe that such organic compounds as may be soluble in the soil water may be used directly by plants, if they are required, in the form in which they exist in decomposing organic matter. Ordinarily, the plant is in competition with soil bacteria for such compounds and may have little opportunity to secure them.

Of considerable interest in this connection is the auximone theory, which credits organic matter with being a source of certain necessary growth-promoting substances that are similar in function to the vitamins in human and animal diets. This is a matter which has received considerable attention in recent years and is now widely accepted as being more than a theory.

When soils become strongly acid, their colloidal organic matter frequently becomes highly peptized and badly dispersed and is carried by the water into the *B* horizon of the soil profile. Here it is precipitated and contributes to the formation of a hardpan layer. If it comes in contact with calcium carbonate, it is precipitated in the form of calcium humate. Similarly, if the surface soil is limed, the humus substances are retained in this precipitated state in the surface soil until they have undergone complete oxidation. The James River of Virginia is formed by the union of two rivers, one of which is said to flow through a limestone region and is clear and sparkling, while the other has its origin in a sandstone region and is colored with organic matter. From the point of union on, the entire body of water is clear, showing the effect of lime as a precipitating agent for such materials. Stream pollution is overcome by passing the waste water from factories through beds of limestone or marl.

THE SOLUTION OF THE PROBLEM OF ORGANIC MATTER

Organic matter may be said to be a by-product of good farming. If large yields of crops are grown, by the use of manure, liming materials, fertilizer, or all three, the residues of these large crops provide adequate amounts of organic matter for the soil, if the crops are grown in suitable rotations. Manifestly, this cannot be accomplished when clean-culture crops are grown continuously. The importance of the sod crops, in so far as the soil is concerned, lies in their contribution to its supply of organic matter. Clovers and grasses are particularly important in this connection. Weeds are an important supplementary source of organic matter.

In market-garden and truck-crop farming, the problem is somewhat more complicated. Most of the soils on which such crops are grown are sandy loams, and these are in especial need of large amounts of such materials as well-rotted manure. If the supply of this is limited, it is then necessary to adopt a policy of growing catch crops and winter cover crops. It may be desirable to set aside a certain portion of the land each year for the purpose of renewing its supply of organic matter by the growing of such a crop as sweet clover. Something can be done to augment the supply of manure by composting leaves, sod, and plant refuse materials, or by the production of synthetic manure, but these are of somewhat limited usefulness except in very small-scale gardening or in the growing of flowers.

Of particular significance is the discovery that fertilizers, even though they may contain no organic matter, are one of the most fruitful means of adding organic matter to soils, by reason of the more abundant residues and roots of crops that have been liberally treated with them. Keeping the soil adequately supplied with lime or limestone is a means both of increasing the amount of residues of crops and of saving, to the soil, humus that might otherwise have been carried into the subsoil by the gravitational water.

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CHAPTER XIV

ROTATING CROPS

The explanation of the good effects of rotation on crop yields is to be found largely in the economy of the resources of the soil and in the control of diseases, insects, and weeds affecting the crops grown. An additional reason for rotating crops lies in the possibility of economizing in the use of labor. Thus, in the common rotation of a cultivated crop, a small grain, and a hay crop, cultivation for a season helps to eliminate weeds; the hay crop is usually a legume which secures at least part of its nitrogen from the air; and the soil is plowed only once in three years.

SOME TYPICAL CROP ROTATIONS

The desirable and undesirable features of the various rotations become apparent as one studies some typical examples. All of those listed below are in common use in the localities indicated.

TABLE 68

STANDARD CROP ROTATIONS

Norfolk, England	New England	Corn Belt	Cotton Belt	Special Crop	Truck Crop
Wheat	Corn	Corn	Cotton	Tobacco	Tomatoes
Barley	Oats	Oats	Corn*	Wheat	Peas*
Roots	Clover	Wheat	Oats*	Clover	Cabbage*
Clover	Timothy	Clover	———†	———†	Potatoes*
———†	Timothy	———†	Cotton	Tobacco	———†
Wheat	———†	Corn	Corn*	Wheat	Tomatoes
Barley	Corn	Oats	Oats*	Clover	Peas*

* Catch crops, for green-manuring purposes, may be grown at the periods indicated. In the Cotton Belt rotation, Austrian peas are employed. In the rotation of truck crops, supplemental truck crops are commonly grown instead of the catch crops.

† This signifies the end of the rotation, after which the crops are repeated.

The examples given are only a few of many rotations that are being followed. They serve to point out some of the problems that are involved in the choice of a rotation, in which consideration must be given to the market requirements and to the economy of labor, as well as to the well-being of the crops themselves. Thus, in the Norfolk rotation, it is necessary to plow the land three years out of four. The New England rotation takes advantage of the good effects of a legume crop only once in five or more years. Three out of the four crops in the Corn Belt rotation are grain crops having much the same soil requirements. The Cotton Belt rotation fails to take advantage of a sod crop as a means of accumulating organic matter. Not enough time elapses between the recurrence of any given crop in the special crop rotation to

FIG. 21. Crop rotation is particularly important in market gardening and truck cropping as a means of controlling insects and diseases.

permit of the adequate control of parasitic organisms that may harbor in the soil. Large amounts of manure or of green manures are required in the continuous growing of clean-culture crops such as are shown in the truck-crop rotation.

CONTINUOUS CROPPING

It is sometimes necessary or desirable to grow the same crop year after year on the same field. This is often true for such perennials as alfalfa and timothy. In hilly regions, with a limited acreage of level bottom land, it may be desirable to grow corn every year on the lowlands and to leave the hills in hay crops and pasture. Newly drained swamp land may be planted continuously to some cultivated crop requiring large amounts of nitrogen until such time as the excessive quantities of this element that are made available have been removed from the soil. In the typical wheat-growing regions, wheat may be the only crop for which there is any market demand. Similarly, in other localities, high prices for some given crop may make continuous cropping desirable, at least for a few years.

One of the most interesting experiments of continuous cropping is that with wheat on the Rothamsted Experimental Farm at Harpenden, England. On the Broadbalk field on this farm, wheat has been grown every year since 1844. The soil is a cherty clay loam fairly liberally endowed with the mineral elements, and contains an abundance of carbonate of lime. The climatic conditions in England are generally very favorable for wheat, the average acre yield for the ten-year period immediately preceding the first World War being approximately 32 bushels. Nevertheless, it is somewhat surprising to note the rather high yields of wheat, grown continuously, on those portions of the field that have been liberally manured or treated with fertilizers, as recorded in Table 69.

TABLE 69

ACRE YIELDS OF WHEAT GROWN CONTINUOUSLY AT ROTHAMSTED

Periods*	Unmanured, Bu.†	Manured,‡ Bu.	Fertilized,§ Bu.
First	17.2	28.0	....
Second	15.9	34.2	36.1
Third	14.5	37.5	40.5
Fourth	10.4	28.7	31.2
Fifth	12.6	38.2	38.4
Sixth	12.3	39.2	38.5
Seventh	10.9	35.1	37.2
Eighth	9.1	27.1	27.4

* Ten-year periods.

† An English bushel equals 1.032 American bushels.

‡ Fourteen tons annually.

§ 1392 pounds annually, containing 106 pounds nitrogen, 66 pounds phosphoric acid, and 96 pounds potash, together with 200 pounds sodium and magnesium sulfates.

Notwithstanding the favorable opportunities enjoyed by parasites and weeds, the yields have been maintained at high levels by the use of liberal amounts of manure and fertilizer. Even on the unmanured plot, the average yield by decades has exceeded 10 bushels an acre until the last ten years, during which there were several very unfavorable seasons. No mention is made in the literature of any especial difficulty with plant diseases or insects, the chief trouble being that caused by weeds, of which the black bent grass (*Alopecurus agrestis*) is one of the most troublesome. This weed was first observed in 1869 and became a very serious pest during the wet seasons of 1878 and 1879. Finally, in 1904 and 1905 and again in 1914 and 1915, the halves of the plots were alternately fallowed. Hand weeding is necessary every season.

THE DISEASE FACTOR IN CONTINUOUS CROPPING

There are a considerable number of fungous diseases which may increase in destructiveness each year under conditions of continuous cropping, by reason of the fact that the soil becomes contaminated with the spores or mycelia of the fungus producing the disease. The nature of the crop and the climatic environment under which it is being grown determine the extent to which injury from disease may be increased by growing the same crop each year on the land. Among the crops that are most seriously affected by fungous and bacterial diseases are flax, alfalfa, red clover, cabbage, onions, and potatoes. The first-named is frequently mentioned in the literature in this connection, it having been found that the flax wilt organism (*Fusarium lini*) is usually very destructive in its effects whenever flax is grown in successive years on the same soil. Corn, oats, wheat, timothy, and cotton are not so seriously affected by the disease factor, as a result of continuous cropping, as are the crops mentioned above.

While crop rotation helps to keep disease organisms under control, nevertheless many of them survive in the soil for such a long period of time that something more than rotation is essential. Selection and breeding for disease resistance offer the most promising possibilities in this connection. However, in the absence of disease-resistant strains of crop plants and in preparation for those years in which the climatic conditions may be exceptionally favorable for some particular disease-producing organism, the rotation principle merits more consideration than is often given it.

ROTATION AS RELATED TO ECONOMY OF PRODUCTION

In the continuous-wheat experiment at Rothamsted, high average acre yields are produced, in spite of any bad effects of continuous cropping, by the use of liberal amounts of manure or fertilizers. Yet the amounts of manure and fertilizer that are employed to produce these yields are much greater than are required for equally high yields when wheat is grown in rotation with other crops. In the Agdell field nearby, on which the Norfolk rotation has been followed, the average yield of wheat on the unmanured plot, for every year in which it has appeared in the rotation since 1851, has been almost exactly twice as many bushels an acre as were produced on the unmanured, continuous-wheat plot during the same years. Similarly, the use of one-third as much fertilizer, of practically the same analysis, has resulted, on the rotation plot, in an average yield of wheat one and a half times as great as that produced during the same years on the best fertilizer plot of the continuous-wheat series.

A variety of explanations for the better yields with rotation may be given. The soil investigator would suggest the effect of the legume crop in connection with the supply of available nitrogen, the more nearly equal distribution of the mineral losses from the soil, the better control of competing weeds and of parasitic soil organisms, the checking of losses by leaching and erosion, and the addition of more organic matter by the growth of clover.

Some additional evidence on the economy of production effected by rotation is given in the following data showing the average acre yields over a thirty-year period in a comparison of continuous cropping and rotation.

TABLE 70

Comparison of Yields in Rotation and Continuous Cropping (Miller)

Cropping System	Corn, Bu.	Oats, Bu.	Wheat, Bu.	Clover, Cwt.	Timothy, Cwt.
6-year rotation*	41.5	27.2	20.1	21.7	24.4
4-year rotation	38.5	27.9	23.6	26.1	....
3-year rotation	32.6	....	14.4	19.1	....
2-year rotation	....	....	18.4	29.7	....
Corn continouusly	20.9	....	....	....	....
Oats continuously	....	16.9	....	....	....
Wheat continuously	....	....	9.5	....	....
Clover continuously	....	....	....	24.3	....
Timothy continuously	....	....	....	....	25.7

* Timothy was allowed to stand for two years in this rotation.

EFFECTS OF CROP PLANTS ON THOSE THAT FOLLOW

It will be recalled that the toxicity theory of soil unproductiveness was based on the assumption that plants excrete substances during growth that are toxic to other plants, particularly to those of the same species. Subsequent investigations indicate that the only excretory product of plant roots which might be assumed to cause injury to themselves or to other plants is carbon dioxide. On the other hand, the nature of the products resulting from the decomposition of plant residues in soils varies considerably, depending upon the species of plant from which these residues are derived, the physical characteristics of the soil, and the moisture and other conditions that obtain in the soil.

It is not illogical to believe that some products of decomposition of plant residues may have toxic effects. Thus, salicylic acid and vanillin have been extracted from soils, and experiments with these compounds indicate that they are injurious to plants when present in very dilute concentrations. The nature of the crop residues would determine the quantity of these and similar toxic substances that might be produced in the soil. It is possible, also, that the growing of a crop may so change the balance of the nutrient elements in the soil solution as to make it toxic to another crop plant, whether it be of the same or of some different species. Thus, the growing of a crop that requires large amounts of calcium, on a soil that is already slightly acid in reaction, tends to cause an increase in the concentration of the H and Al ions and to reduce the content of soluble phosphorus.

There is considerable evidence which indicates that, under certain conditions, the nature of the previous crop has an important relationship to the yield of the crop following. A rather remarkable example of differences in the yields of a common crop, following the growth for two successive years of a considerable variety of other crop plants, is given in the following table. The three crops that were common to all plots in this experiment were onions, buckwheat, and alsike clover. Each of these was sown over the entire area, following a two-year period in which the land was divided among the various other crops that were grown in the test.

TABLE 71

Effect of Crop Plants on Acre Yields of Those Following (Hartwell)

Previous Crop	Onions, Bu.	Buckwheat, Bu.	Alsike,* Cwt.
Onions	289	20.8	77
Potatoes	110	22.7	70
Beets	72	20.5	73
Turnips	99	33.8	74
Cabbage	88	20.2	73
Buckwheat	112	13.0	70
Corn	286	5.4	76
Millet	319	4.4	66
Oats	346	15.0	73
Rye	187	21.5	85
Red top	524	9.6	86
Timothy	362	4.4	76
Alsike clover	415	7.3	50
Red clover	249	7.5	53

* Alsike clover was grown for two years.

The soil on which the above tests were made is somewhat acid in reaction. The indications are that, if the soil had been adequately limed, the differences in yields would not have been so marked. It is of interest to note that the yield of onions (a crop that is very sensitive to acid soils) is largest following red top (a crop that is well adapted to acid soil conditions). Since a large proportion of the soils of the United States are being farmed under conditions of deficiency of one or more of the nutrient elements, and most of them receive less liming materials than are required for optimum reactions for the crops grown, it would seem probable that the selecting of the crops for the rotation with reference to their effects on each other, and the order of their arrangement in the rotation, merit further study.

CROP SEQUENCE IN ROTATION

It is a matter of common knowledge that the yield of wheat following tobacco or potatoes is considerably higher than it is after corn. Some data of interest in this connection are found in the average yields of wheat secured in a nine-year test on a Wooster silt-loam soil that received a liberal standardized treatment of manure, limestone, and superphosphate. The yields of wheat following potatoes, clover, oats, corn, and soybeans were 37.35, 36.17, 35.49, 33.10, and 32.62 bushels an acre, respectively. An examination of the soil during the autumn months showed that the quantities of nitrates that were present in the soils of the several plots, following the growth of the above crops, were in the order of the subsequent yields of wheat. In the ordinary corn, oats, wheat, and clover rotation, it is possible to change the sequence in such ways as to arrange six different rotations, each of which is feasible and might be good practice if increased yields could be effected by the change.

The fact that differences in yield, as related to the previous crop, are magnified on acid soils would make it appear advisable to arrange the crops in the descending order of their need for lime, once it had been applied. The question also arises as to whether it is desirable to attempt to fit into the same rotation crops having widely different lime requirements, as, for example, oats and alfalfa. In areas of acid soil, it is easily possible that one field should be set aside for alfalfa and employed almost exclusively for that crop for some years, with liberal use of limestone, potash, and phosphate, while the remainder of the farm might be devoted to a rotation of other crops that are less sensitive to acid soil conditions and for which less lime need be applied. The popularity of sweet clover as a green-manure crop may possibly wane when the soils become more acid, if too much difficulty is experienced in maintaining the reaction of the soil at a point that is suited to the needs of this crop. On the other hand, it seems probable that the value of these crops for soil-improving purposes may justify the use of enough limestone to guarantee their successful growth in the rotation. In northern Europe, it is a common practice to grow alfalfa on the land for a three-year period out of every ten or twelve years, the soil being limed for the alfalfa crop.

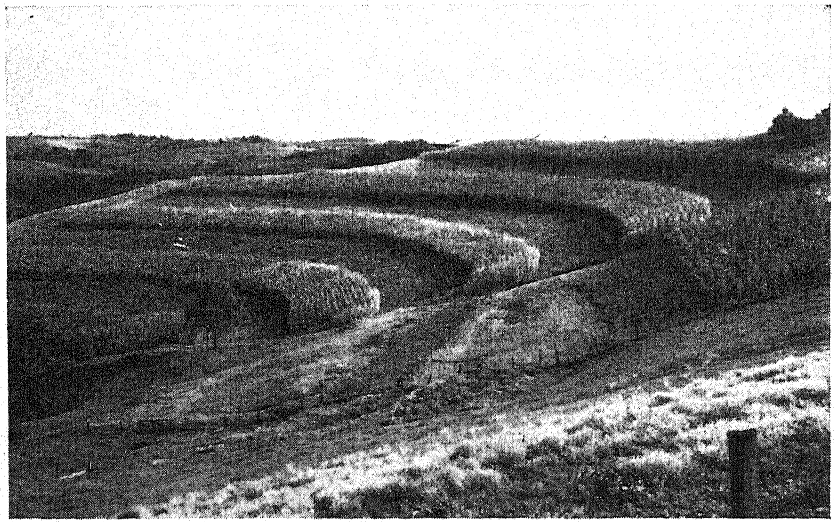
GROWING CROP PLANTS IN ASSOCIATION

Since the soil varies in its characteristics from place to place in the same field, and since crop plants differ in their requirements, it seems logical to sow a mixture of seeds of such plants as are to be used for feeding purposes. Under natural conditions, plant associations are the rule, the members of the association being such as have, in general, the same soil and climatic requirements but differ sufficiently to permit of their taking advantage of variations in the soil or in other conditions that obtain. Deep-rooted plants are found growing in association with shallow-rooted ones; plants that grow best in sunshine are associated with those requiring shade; while many plant associations consist of species that reach maturity and produce seed at different times of the year.

The mixtures that have been most frequently tried in general farming are oats and barley for grain; corn and soybeans for ensilage and for hogging down; and the usual combinations that are used for lawn, pasture, and hay purposes. So far, little has been shown to be gained by any of these mixtures but the last-named group. Oats and barley seem to have too much similarity in their requirements. Corn and soybeans can be grown in association to advantage under conditions of abundant supply of moisture, nitrates, and mineral nutrients. Very often the effect of the soybeans on the corn is much the same as that of weeds. For grass and hay purposes, the mixtures are more effective than any one of them when sown alone. The common alfalfa, red clover, alsike clover, and timothy mixture meets the requirements under conditions of considerable variation in the soil and of uncertainty as to the weather. There is some evidence that, when non-legumes and legumes are grown in association, the former contain higher percentages of nitrogen than when grown alone. As the level of crop yields is raised by more intensive farming, less can be expected of crop mixtures that are designed to take advantage of inequalities of the soil or year-to-year variations in the climatic conditions.

IMPORTANCE OF LEGUMES IN ROTATIONS

The importance of the legumes in general farming rotations and for green-manuring purposes in the more specialized types of farming is such that careful attention must be given to the control of any factors that tend to prevent their successful growth. The legume plants vary in their requirements to such an extent that one may be chosen to fit almost any conditions that may obtain. It happens, however, that alfalfa, sweet clover, and red clover are usually grown in preference to most of the others, for hay and for soil-improving purposes, in those



Soil Conservation Service

FIG. 22. Holding the hillside, with corn on the contours and hay in between.

regions to which these crops are adapted. In the southern states, crimson clover and cowpeas are very popular for these purposes. Analyses of the legume plants, together with many years of experimenting with them, have shown the necessity of keeping the soil well supplied with lime and with the mineral nutrients, if the legumes are to function properly in their capacity of accumulating nitrogen and organic matter from the air.

Considerable difficulty is experienced with certain diseases and insects, some of which are troublesome only on certain species of legumes. Lengthening the rotation or substituting different legumes with each course of the rotation helps to eliminate this difficulty. Thus, in the ordinary three-year rotation, the clover crop may be either alfalfa, sweet clover, red clover, or alsike clover, depending upon the reaction, moisture conditions, and the supply of mineral nutrients in the soil, and upon the difficulty that is being experienced with insects and diseases. It is only in the more intensive systems of agriculture that commercial nitrogen can be entirely substituted, with economy, for that secured from the air through the growth of legumes; and even then the legume plays an important part as a conditioning agent in the soil.

THE INSUFFICIENCY OF CROP ROTATIONS

The rotation of crops is not a means of adding any of the mineral elements to soils. On the contrary, it very definitely increases the rate at which these elements are removed from the soil, by reason of the larger crops grown. Its chief value, from the point of view of soil conservation, lies in providing a better opportunity to contribute to the supply of combined nitrogen and carbon in the soil, and in preventing unnecessary losses by leaching and erosion.

Coupled with a system of livestock farming in which the crops are fed and their nutrient elements are in large part returned to the soil, or coupled with adequate provision for the return of the essential mineral elements in commercial forms, rotation helps to maintain the productivity of the soil at a high level. Failure to take into consideration the mineral requirements of these larger yields that are made possible by rotation may soon result in the exhaustion of the available mineral nutrients and in a reduction in yields, even on the best of soil and with the most desirable rotations. An example of this is afforded in the following data from an experimental test that had been in progress for forty years with a rotation of corn, oats, wheat, and clover, grown on

TABLE 72

ACRE YIELDS OF CROPS IN ROTATION ON UNMANURED SOIL (NOLL)

Period*	Corn, Bu.	Oats, Bu.	Wheat, Bu.	Clover,† Cwt.
First	50.0	40.2	16.3	28.3
Second	56.8	41.4	10.3	35.2
Third	45.3	37.0	18.7	34.3
Fourth	35.5	28.2	16.9	27.5
Fifth	30.4	22.3	9.5	18.1
Sixth	34.7	25.7	10.1	24.8
Seventh	24.2	26.0	13.7	18.1
Eighth	26.5	29.1	13.7	16.9
Ninth	26.0	33.4	10.1	15.8
Tenth	28.6	27.6	8.7	16.3

* Four-year periods.

† A mixture of clover and timothy is sown for hay.

a naturally productive clay-loam soil of the Hagerstown series on the Pennsylvania State College farm.

OTHER ROTATION RELATIONSHIPS

Crop yields are not always the best measure of the efficiency of a rotation. Thus, in the growing of tobacco, the rotation is adjusted to the type of tobacco to be grown. If dark tobacco is desired, a rotation of tobacco, wheat, grass (two years), corn, cowpeas, and red clover is suggested; while for bright tobacco the clover crop is omitted. With bright tobacco the yields are larger following clover, but the quality is inferior. In the Connecticut Valley, rotation with the tobacco crop is dispensed with entirely by reason of the necessity of controlling root rot which seems to be favored by the presence of the residues that are left behind in the soil following the growth of grass or hay crops.

One of the most serious problems involved in practice is that of crop failures which make necessary certain changes in crop sequence and quite often reduce the effectiveness of the rotation scheme. Corn may follow corn, if oats fails. The corn, wheat, and clover rotation may be changed to corn, wheat, corn, wheat, and clover, if the clover freezes out. The clover field may lie over a second year and be mostly timothy, if a new seeding does not survive the summer drought. These irregularities in the rotation may not be particularly serious, if they happen only occasionally, but the evidence indicates that on many farms failures occur time after time, with resulting serious reductions in the yields. The remedy lies in so managing the soil, with reference to the use of tile, manure, liming materials, and fertilizers, that crop failures do not occur except on very rare occasions. Usually, failure is not due to the weather alone but partly to a deficiency or an excess of some factor in the soil, which intensifies the unfavorable conditions.

SOLUTION OF THE PROBLEM OF CROP ROTATION

While economic factors must be taken into consideration in the choice of crops to be grown and in their arrangement in rotations, they should not be allowed to overshadow the fact that rotation is of primary importance as an aid in the maintenance and increase in the productive capacities of soils. In fact, one of the greatest economies that can be effected in crop production is that which is accomplished by putting into operation a systematic scheme of rotation that takes advantage of the differences in the growth requirements of crops, and in their effects, either directly or indirectly, on those which follow.

In general farming, the key crop in the rotation is the hay or pasture crop, which is ordinarily either a legume or a mixture of clover and grasses. Much of the success of these rotations depends upon the extent to which the requirements of the legume crop have been met. It is a matter of common belief that clovers are soil-rejuvenating crops, but their effectiveness in this connection lies almost entirely in their ability to accumulate carbon and nitrogen in such ratios as permit of their rapid decomposition in the soil. Failures of clover crops are entirely too frequent, and indicate a lack of appreciation of the fact that most of these crops have relatively high lime requirements and cannot be grown satisfactorily on soils that are deficient in the mineral nutrients. Sweet clover is somewhat of an exception because of its capacity to forage for phosphoric acid and potash in the soil, but it responds remarkably to these fertilizers. Another equally important fact to remember is that these mineral nutrients are removed from the field with the clover and that as much may be carried away with the harvested crop as is contained in the residues left on the field and in the soil after legume crop is harvested.

In market gardening and truck farming the problem of rotation is very different, since large amounts of manure, lime, and fertilizer are usually applied and the need for equalizing the draft on the soil is not serious. On the other hand, the more frequent reappearance of each crop on the soil complicates the problem of disease control and makes this of primary concern in arranging the crop sequence. Fortunately, this problem is coming more and more under control through the growing of disease-resistant strains of plants and the using of sulfur and lime to regulate the reaction of the soil at critical points for the parasitic organisms.

It seems worthwhile to continue to study the differences in the requirements of crop plants and the nature of their effects on each other, and to take advantage of the facts thus secured in the selection of rotations, in the sequence of the crops to be grown, and in the adjustment of conditions to meet the needs of each crop as it appears in the rotation.

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CHAPTER XV

NITROGEN ECONOMY IN SOILS

There is a fundamental difference between the problems involved in the economy of nitrogen and in that of any other nutrient element. The air above an acre of land is estimated to contain 70 million pounds of this element. From this the soil receives contributions each year, both in the combined nitrogen which is dissolved in the rain and in that which is accumulated by nitrogen-fixing bacteria in the soil. It happens that nitrogen, as the nitrate, is very readily leached from the soil. There is the further possibility of its loss in the elemental form in the process of denitrification, and as ammonia from decomposing manures. The only other element that resembles nitrogen in many of these respects is carbon, but this element is freely absorbed by the leaves of plants and seldom becomes a limiting factor in crop production by reason of deficiency. In general, it may be said that, if the problem of the economy of nitrogen has been solved, the task of maintaining the soil at a high level of productivity has been very materially simplified.

TABLE 73

POUNDS OF NITROGEN IN AN ACRE OF SOIL (HOPKINS)

Soil Type*	0–6⅔ Inches†	6⅔–20 Inches	20–40 Inches	0–40 Inches
Black clay loams	7,230	7,470	3,210	17,910
Brown silt loams	5,035	5,920	3,570	14,520
Brown loams	4,720	6,660	4,150	15,530
Deep-gray silt loams	3,620	2,250	2,280	8,150
Brown sandy loams	3,070	3,920	4,160	11,150
Yellow-gray silt loams	2,890	2,710	3,240	8,840
Gray silt loams	2,880	3,210	3,240	9,330
Drab silt loams	2,800	3,160	3,400	9,360
Yellow fine sandy loams	2,170	2,610	2,730	7,510
Yellow silt loams	2,020	2,050	2,410	6,490
Light-gray silt loams	1,890	1,920	2,100	5,910
Sands	1,440	2,070	3,100	6,610

* These soil types are found in considerable areas in the North Central States.

† This is on the assumption that there are 2 million pounds of soil in an acre for each depth of 6⅔ inches.

THE NITROGEN CONTENT OF SOILS

Soils vary within rather wide limits in the amounts of combined nitrogen contained in them. This is shown in Table 73, in which the extreme quantities of nitrogen in an acre of soil to plow depth are 1440 and 7230 pounds, respectively. What might be called an average productive soil of humid climates contains approximately 3500 pounds of this element in the plowed acre in the form of plant and animal residues. The quantity of nitrogen in the subsoil usually decreases with depth until a point is reached at which it may remain fairly constant. The total amount of nitrogen that is contained in the first 40 inches of soil and subsoil is quite large. While the percentage of this nitrogen that may be changed to the nitrate form in any one crop season is very small and is not directly proportional to the total amount in the soil, yet, under identical systems of soil management, the greater the quantity of nitrogen in the soil, the larger the amount that will be available each year for crop use.

THE NITROGEN CONTRIBUTED BY RAIN

Liebig was of the opinion that the ammonia of the atmosphere, which is carried to the earth by the rain, serves to replace that which is lost from the soil by the removal of crops and in drainage waters. In testing this assumption, Lawes and Gilbert demonstrated that the annual contribution of combined nitrogen in the rain, at Rothamsted, varies between 3 and 5 pounds an acre, amounts that are entirely inadequate to compensate for the losses occasioned by cropping. Subsequent investigation has shown that the quantity of nitrogen which is brought down in the rain may be as much as 10 to 15 pounds an acre, the amount being related to the number of inches of rainfall and to the nearness of industrial plants that consume large tonnages of coal. On the average, it is probably safe to assume that the total yearly contribution of nitrogen in the rain, in humid regions, is 5 pounds an acre, the larger part of which is present in the form of ammonia and nitrates. This serves as a supplemental supply of nitrogen which is sufficiently large to be of considerable importance in the economy of this element when considered from the point of view of long periods of time.

THE NITROGEN FIXED BY NODULE BACTERIA

The good effects of the legume crops in the rotation are due in part to the nitrogen that is accumulated from the atmosphere by the bacteria which inhabit the nodules on their roots. It is somewhat difficult to determine what percentage of the total nitrogen that is contained in the legume plant had its origin in the air and what part of it came from the soil. On the assumption that two-thirds of the nitrogen of red clover comes from the air and one-third from the soil, Hopkins points out that, if a clover crop were grown and removed from the field, the soil would neither gain nor lose in its nitrogen content. This conclusion is based on evidence from the Delaware Experiment Station, which indicates that, of the total nitrogen of the red clover plant, one-third is to be found in the roots and stubble and two-thirds in the harvested crop. If the clover crop is plowed under, the gain in nitrogen, on this assumption, is 40 pounds for each ton of clover hay that the green crop would have yielded. If the clover is harvested as hay, and fed, and the manure that is produced from feeding it is returned to the field, the gain to the soil is 32 pounds of nitrogen for each ton of hay, assuming an 80 per cent recovery in the manure.

Such a simple statement of the quantitative effects of clover or of any legume crop, on the nitrogen content of the soil, is likely to be far from the truth in many cases. Hellriegel and Wilfarth's original experiments show that the entire nitrogen requirements of legumes can be satisfied from the air when they are grown on nitrogen-free sand. Subsequent experiments make it apparent that, in the presence of adequate supplies of available nitrogen in the soil, neither the symbiotic nor the non-symbiotic bacteria are likely to secure any large part of their nitrogen from the air. The rate of fixation, therefore, is determined not only by the degree to which conditions have been made favorable for the growth of the legume and of its supporting bacteria, but also by the extent to which their requirements are satisfied by the nitrogen made available by nitrification in the soil.

Any legume that can be made to produce a rapid vegetative growth on soils that are low in their content of organic matter and nitrogen, by the use of fertilizers which contain little or none of this element, can be expected to accumulate a large part of its nitrogen from the air. This is particularly true if this rapid growth is effected in the cooler portions of the year when the rate of nitrification is relatively slow.

SOME POT EXPERIMENTS ON NITROGEN FIXATION

An interesting and suggestive quantitative study of the fixation of nitrogen under optimum conditions is to be found in the data recorded in Table 74 from some pot experiments with soybeans and cowpeas. In these tests, five crops of the legumes were grown in succession, with vetch as an intervening winter cover crop. The summer legumes were harvested and removed and the cover crops were incorporated with the soil. The data are calculated on the acre basis.

TABLE 74

FIVE-YEAR POT TESTS ON NITROGEN FIXATION (HARTWELL)

Pounds of Nitrogen per Acre	Soybeans*	Cowpeas*
In soil at beginning	3644	3471
In planted seeds	600	265
In added manure and water	71	72
In aerial portion of legumes	1340	1470
In soil at end of test	4820	4492
Gain in five years	1845	2154

* These legumes were harvested. Vetch was used as a winter cover crop that was turned under.

Under conditions that are suitable for pot tests, non-symbiotic fixation of nitrogen is also favored, so that the division of the credit among the several groups of nitrogen-fixing organisms is very difficult. The rate of fixation in the above test was approximately 200 pounds of nitrogen an acre for each legume crop grown. If such an experiment were continued over a longer period of time, a point would soon be reached at which no further accumulation would take place, by reason of the fact that the soil would contain an abundance of available nitrogen.

EFFECT OF INOCULATION ON NITROGEN ACCUMULATION BY LEGUMES

Another method of estimating the amount of nitrogen that is fixed by the nodule bacteria, and one that has frequently been employed, is to compare the amount of this element that is contained in the legume crops of two equal areas of land, of which the soil or seed of one has been inoculated and that of the other has not. An example of such a method of calculating the efficiency of the nodule bacteria is given in the following table. In this test, sweet clover and alfalfa were seeded in April of one year and harvested in June of the year following.

TABLE 75

ACRE INCREASE IN POUNDS NITROGEN IN LEGUMES FROM INOCULATION* (ARNY)

	Sweet Clover			Alfalfa		
	Tops	Roots	Total	Tops	Roots	Total
Inoculated	112	16	128	90	32	122
Uninoculated	10	1	11	11	3	14
Gain for inoculation			117			108

* Seed was sown April 23, and crops were harvested June 22 of the following year.

Neither of these legumes having been previously grown on this land, portions of it were inoculated with soil from other fields on which these crops had been grown successfully. At the time of harvest, the soil was washed from the roots, and records were made of the weights and nitrogen contents, both of the tops and roots.

Not all this increase in nitrogen accumulation can be credited to the activities of the nitrogen-fixing bacteria. By reason of the better-developed root systems and the longer growth of tops of the inoculated plants, their capacity to absorb additional nitrogen from the soil was also increased. This is on the assumption that more available nitrogen was present in the soil than was taken up by the roots of the uninoculated legume plants.

NITROGEN ACCUMULATION IN THE ABSENCE OF LEGUMES

The rate at which nitrogen is accumulated in soils in the absence of legume crops has also been studied. The capacity to fix atmospheric nitrogen is known to be a function of several species of aerobic azotobacter, of the anaerobic *Clostridium pastorianum*, and of the nodule bacteria of legumes, even when they are not associated with their hosts. It is also believed that many of the other microscopic forms of plant life in soils are able to secure their nitrogen from the air under conditions of scarcity of soluble nitrogen.

It has frequently been shown that, if a soil is liberally treated with limestone and superphosphate, if some soluble carbohydrate is supplied to it and if the conditions of aeration and moisture supply are kept at the optimum by laboratory control, nitrogen accumulation is effected at the rate of 100 pounds or more in 2 million pounds of soil in a period of three weeks. This indicates that, even under field conditions, nitrogen fixation by non-symbiotic bacteria may take place at a very rapid rate over short periods of time if conditions are favorable.

NITROGEN ACCUMULATION UNDER FIELD CONDITIONS

Some interesting data on nitrogen accumulation under field conditions are given in Table 76. In this investigation two areas of land on the Rothamsted Experimental Farm were allowed to run wild for a period of twenty years. Samples of soil chosen to a depth of 27 inches before and after this period were compared as to their nitrogen content.

Nitrogen was accumulated in the Geescroft field, in the almost entire absence of legumes, at an annual rate estimated at 44 pounds an acre. This would appear to have been accomplished largely through the ac-

TABLE 76

NITROGEN ACCUMULATION* IN SOILS OF UNDISTURBED AREAS (HALL)

Field	1881–1883	1904	Gain
Broadbalk:†			
First 9 inches	2924	3920	996
Second 9 inches	1898	2579	681
Third 9 inches	1569	2265	696
Geescroft:‡			
First 9 inches	2219	3537	618
Second 9 inches	1995	2238	243
Third 9 inches	1612	1760	148

* Nitrogen in pounds per acre at periods indicated.
† Legumes 25.31 per cent of vegetation in 1904.
‡ Legumes 0.43 per cent of vegetation in 1904.

tivities of the non-symbiotic, nitrogen-fixing bacteria, although it is possible that other agencies may have been responsible, in considerable part, for this accumulation of nitrogen since insects, mice, and birds tend to migrate to such areas.

INOCULATION TO INCREASE THE RATE OF FIXATION OF NITROGEN

In Hellriegel and Wilfarth's experiments, it was noted that inoculation was not accomplished in certain cases unless the soil extract was secured from a soil on which that particular legume had previously been grown. After some years of investigation of this problem, the conclusion has been reached that there are either several species of the nodule bacteria or that, by reason of their long association with the different species of legumes, they have become adapted only to the species or family with which they have long been associated. For this reason, there are many failures in the growing of legumes for which no explanation is available except that the crop is new to the field in which it is planted, and that the necessary species or adaptation forms of nodule bacteria are not present in the soil. The difficulty has often been overcome by the use of soil that has been taken from a field on which that species of legume has been previously grown, or by the use of inoculating material that has been prepared from pure cultures of the bacteria secured from the nodules of the same legume species.

Frequently, successful inoculation can be accomplished by sowing a few hundred pounds of inoculated soil on an acre or by moistening the seed with a suspension of the inoculated soil in water. Usually, it is more convenient and more satisfactory to use commercial cultures, most of which have been found to be reliable. The United States Department of Agriculture and several of the state experiment stations have been distributing pure cultures of nodule bacteria to farmers at cost. In addition to sterilized soil, a great variety of culture media have been suggested for use in connection with the growth and distribution of these cultures, of which that shown in Table 77 is an example.

TABLE 77

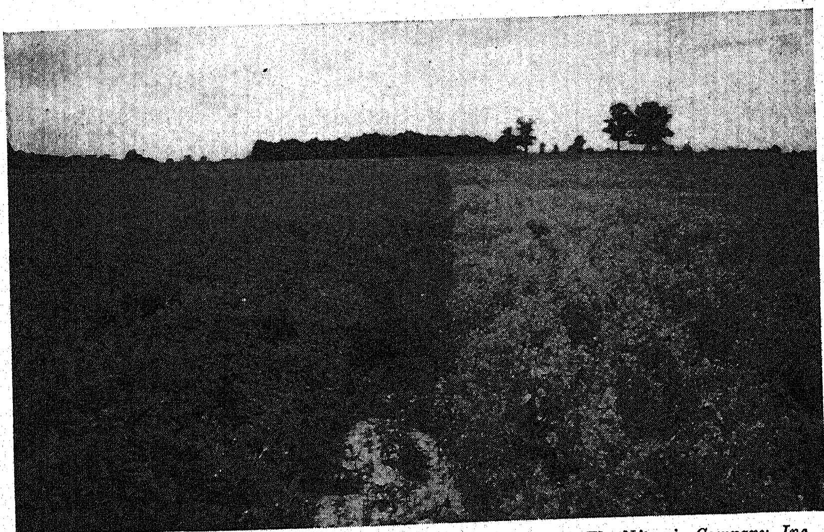
CULTURE SOLUTION FOR NODULE BACTERIA*

Tap Water	1 Liter
Potassium phosphate	1.0 gr.
Magnesium sulfate	0.2 gr.
Cane sugar	10.0 gr.

* The reaction of the solution is kept slightly acid.

EFFICIENCIES OF VARIOUS BIOTYPES OF NODULE BACTERIA

It has been shown that the various strains of nodule bacteria that are capable of producing nodules on the same legume crop differ in their

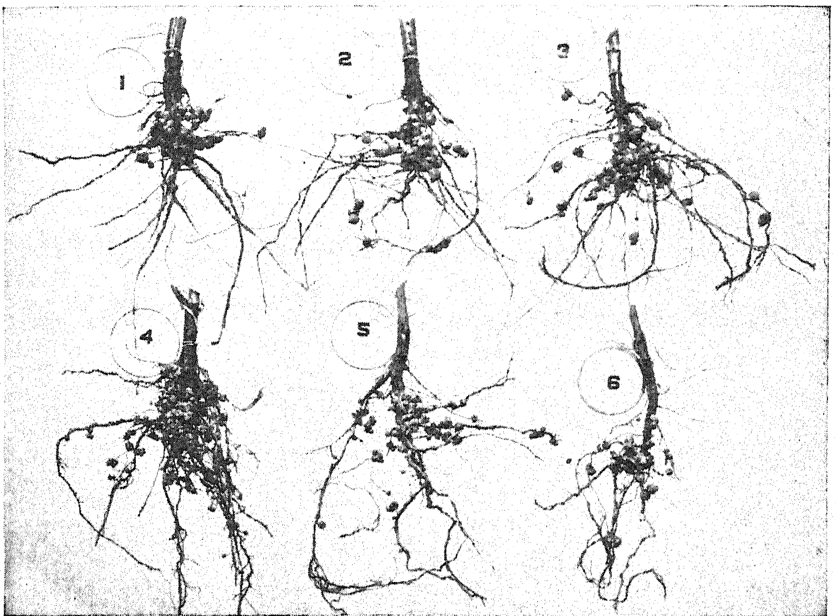


The Nitragin Company, Inc.

(a) (b)

FIG. 23. Effect of inoculation with improved strain of nodule bacteria. (a) Inoculated peas. (b) Uninoculated peas.

efficiencies in accumulating atmospheric nitrogen. In a study of a number of different strains of rhizobia isolated from soybean nodules, it was found that they could be arranged into groups which were identical morphologically but which differed in their physiological characteristics. Table 78 gives the results of three years' investigations of the nitrogen-fixing capacities of these six strains.



W. H. Wright, Wisconsin Agr. Exp. Sta.

FIG. 24. Difference in size, number, and arrangement of nodules on roots of soybeans, resulting from inoculations with six different strains of bacteria.

TABLE 78

COMPARISON OF SIX STRAINS OF SOYBEAN BACTERIA (WRIGHT)

Strains of Bacteria	Dry Weights of 50 Plants, Grams	Nitrogen Fixed in 50 Plants, Grams
1	854	14.31
2	870	16.50
3	866	14.29
4	846	15.19
5	674	6.19
6	696	6.49

This indicates that there are two distinct groups, or biotypes, of the nodule bacteria of the soybean in the six strains that were studied, one of which is much more efficient than the other in fixing atmospheric nitrogen.

INOCULATION OF NON-LEGUME PLANTS

It is a well-known fact that certain non-legume plants bear nodules on their roots. It was thought that the bacteria contained in these nodules belonged to the same species as those that produce nodules on the roots of legumes, but this has been disproved. Attempts have been made from time to time to inoculate such plants as corn, tomatoes, beets, wheat, and others with the nodule bacteria of legumes, but without success. In spite of the failure to produce nodules on these crops, beneficial results have been occasionally noted as a result of the inoculation of the seed. The explanation of this is wanting, but it probably lies in some other effect than that resulting from a symbiotic relationship between the nodule bacteria and the non-legume plant.

It has been shown that the nodule bacteria have the capacity to fix atmospheric nitrogen, even when they are not associated with legumes, and that their efficiency is increased under conditions in which the nitrogen, as it is accumulated, is removed from the medium on which the nodule bacteria are growing. This requirement would seem to be met if the nodule bacteria were living in the presence of the growing root system of a non-legume plant which was utilizing the soil nitrogen as it became available.

INOCULATION OF SOILS WITH AZOTOBACTER

The azotobacter seem to be rather widely distributed in soils. Little if anything seems to be gained by artificial inoculation with pure cultures of these bacteria. It has been shown that under unfavorable conditions as to the reaction of the soil, the azotobacter tend to disappear, but when the soil is limed they reappear. Probably they continue to exist at points at which the reaction of the soil is favorable or where particles of limestone may still persist, even though the major portion of the soil is acid. These points serve as centers from which the azotobacter, and nodule bacteria as well, spread when the soil conditions are made favorable for them. The effects of cultivation and of the action of wind and water are such as to aid in the re-inoculation of the soil.

On the other hand, it seems likely that further study of this problem will show possibilities in the inoculation of soils with azotobacter, as well as with other species of nitrogen-fixing bacteria, under certain favorable conditions, especially if strains are used that have been selected by reason of their efficiency in this capacity.

EFFECT OF REACTION ON NITROGEN-FIXING BACTERIA

The bacteria that have to do with the accumulation of nitrogen vary considerably in their requirements as to soil reaction. The same is true of the bacteria that transform the nitrogen of proteins into ammonia and nitrates. In ammonia formation, the process is carried out by bacteria, if the soil tends toward the neutral point, and by fungi under conditions of high acidity. The nitrifying bacteria grow best under slightly alkaline conditions, but nitrates are also produced in the acid soils. Most azotobacter gradually disappear from the soil when the reaction becomes more acid than *p*H 6. Studies of the various strains of legume bacteria indicate considerable variations in efficiency, not only among those that produce nodules on the different legume species, but also among the different biotypes isolated from the same species of legumes.

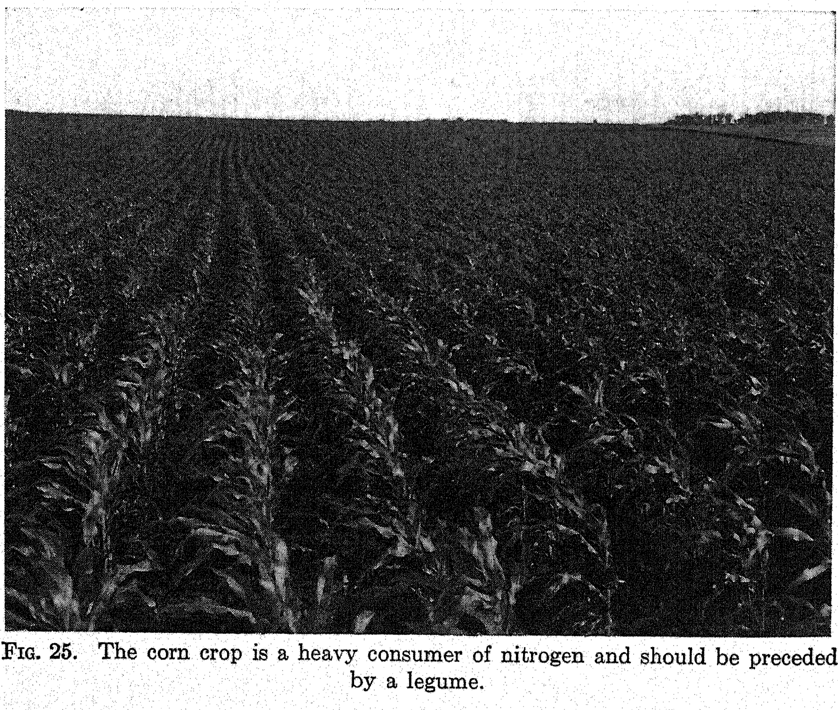


FIG. 25. The corn crop is a heavy consumer of nitrogen and should be preceded by a legume.

In general, the sensitiveness of the nodule bacteria to acid soil conditions is believed to correspond to that of the several legumes on which they produce nodules. The various strains of nitrogen bacteria are arranged in Table 79 according to the critical *p*H of each when grown in solution cultures.

TABLE 79

SENSITIVENESS OF NITROGEN-FIXING BACTERIA TO ACIDITY (FRED)

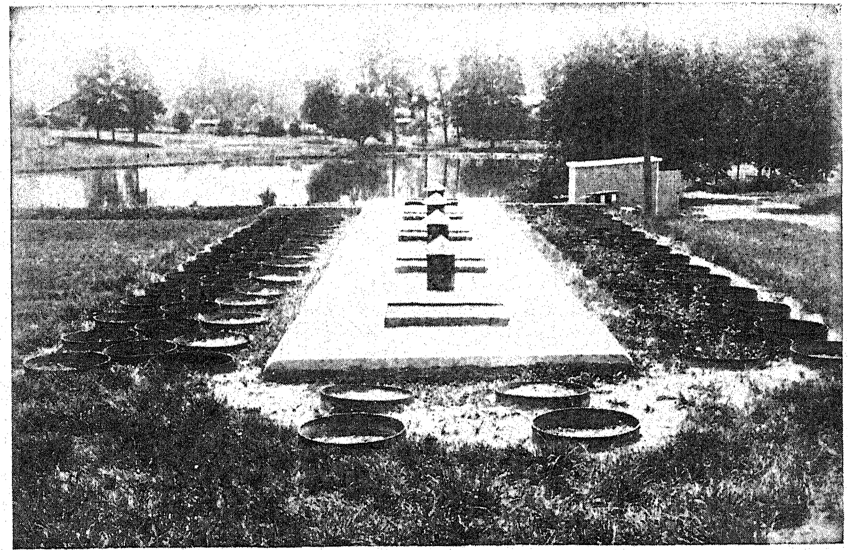
Groups of Bacteria	Sensitiveness	Critical pH
Azotobacter	Extremely sensitive	6.4
Alfalfa and sweet clover	Very sensitive	4.8
Garden pea, field pea, and vetch	Very sensitive	4.6
Red clover and common beans	Sensitive	4.1
Soybeans and velvet beans	Less sensitive	3.2
Lupine	Least sensitive	3.1

OPTIMUM CONDITIONS FOR NITROGEN FIXATION

In general, the conditions in the soil are most favorable for the nitrogen-fixing organisms when the reaction of the soil approaches the neutral point. The azotobacter are much more sensitive to acid soil conditions than are certain of the groups of legume bacteria, but even those legumes that grow quite satisfactorily on fairly acid soil produce much larger yields and show evidence of increased nitrogen fixation by their associated nodule organisms when the soil is limed. Nitrogen fixation is also very markedly increased by the use of liberal amounts of fertilizers that are high in phosphorus and potassium. In fact, the requirements for rapid fixation of nitrogen by soil bacteria are much the same as those for the rapid growth of most plants, with two important exceptions. The nitrogen-fixing bacteria require an abundance of available carbohydrate, supplied either by the soil or by the plant with which they are associated. They do not function satisfactorily in the presence of soluble nitrogen, but apparently consume the combined forms of nitrogen rather than the nitrogen from the atmosphere. The possibility of breeding highly efficient strains of both symbiotic and non-symbiotic, nitrogen-fixing bacteria for inoculating purposes is of great importance.

NITROGEN LOSSES IN DRAINAGE WATERS

Under field conditions, there may be considerable opportunity for the loss of nitrogen as calcium nitrate in drainage waters. Where the soil is acid, there may be some additional loss of nitrogen in the form of soluble humus substances. Ammonia is not carried away as such in the drainage since most soils have very marked capacities to adsorb this compound from solution. The total annual loss of soil nitrogen will be determined by the crops that are being grown, the extent to which the soil is kept occupied by crops, the amount of rainfall, the physical characteristics of the soil, and the amount of available nitro-

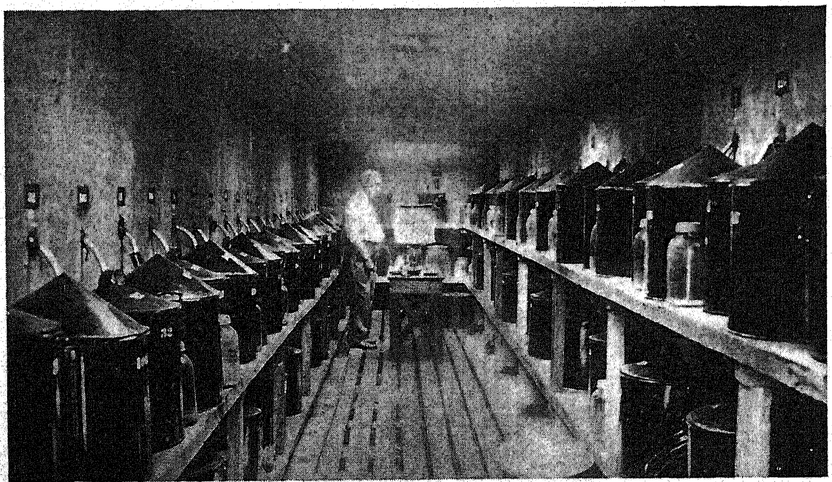


H. H. Hill, Virginia Agr. Exp. Sta.

FIG. 26. The lysimeter method of study (view above ground).

gen that is produced in the soil or added to it in the form of manure or fertilizers.

Some interesting evidence on the rate of loss of nitrogen from soils, as related to the cropping system, is afforded by lysimeter experiments, data from one of which are recorded in Table 80. Dunkirk clay-loam



H. H. Hill, Virginia Agr. Exp. Sta.

FIG. 27. View of interior cave, lysimeter method of study shown in Fig. 26.

and Volusia silt-loam soils, originally containing 0.134 and 0.145 per cent nitrogen, respectively, in the surface foot of soil, were used in these tests. The soil was transferred from the field to the lysimeters with as little disturbance as possible, the several horizons of soil being placed in the tanks in the order in which they occurred in the field.

TABLE 80

POUNDS OF NITROGEN REMOVED PER ACRE IN CROPS AND DRAINAGE (LYON)

Crops Grown	Dunkirk Clay-loam Soil		Volusia Silt-loam Soil	
	In crops	In drainage	In crops	In drainage
Maize	144	12	32	15
Oats	73	9	29	10
Mixed grasses	46	1	..	..
Timothy	49	3	..	..
Timothy and clover	73	2	..	..
Peas	..	..	81	12
Bare tanks	..	93	..	54

It seems evident that the loss of nitrogen may be considerable under conditions of clean cultivation. The loss is very much reduced if a crop is being grown, particularly if that crop covers the entire area of soil, as it usually does with the grass and hay crops.

NITROGEN LOSSES BY DENITRIFICATION

It has been shown that certain species of bacteria have the power of liberating the element nitrogen from the nitrite and nitrate forms. The requirements for this process are the presence of carbonaceous materials and anaerobic conditions. It is conceivable that these conditions might occur in the soil if nitrification has taken place and the soil has later been saturated with water for a considerable period of time. For this reason, nitrates are never used as fertilizers for paddy rice.

Denitrification may also take place in a manure heap, if the nitrates that may be produced near the surface of the heap are washed into the interior, where anaerobic conditions obtain. Ordinarily, little denitrification occurs in manure as it exists in the manure shed because the conditions are not favorable for the production of nitrates. It is believed that most of the reduction in the nitrate content of soils that has been observed after the use of straw and raw manure is not the result of denitrification, with the consequent loss of elemental nitrogen, but is due to the utilization of these nitrates for purposes of nutrition by the bacteria that effect the decomposition of the cellulose.

NITROGEN REMOVED BY CROPS

The amount of nitrogen that is removed from the soil with the harvested crop is quite variable, depending upon the species or variety of crop, the age at which it is harvested, the acre yield, and the quantity of nitrogen that has been yielded up by the soil in a form which is available for crop use. In applying the analytical data, which are given for the various crops, to the determination of the nitrogen losses through crop removal in any given case, all these factors must receive consideration. There is the additional complication, with legume crops, that a part of the nitrogen which is contained in them had its origin in the air. Table 81 gives the approximate nitrogen content of the various groups of crops, or of the portions of them that are harvested.

TABLE 81

POUNDS OF NITROGEN IN 1000 POUNDS OF CROP

Legume seeds	30 to 60
Oil-bearing, non-legume seeds	25 to 40
Legume hays	20 to 30
Tobacco leaves (cured)	20 to 25
Cereal grains	15 to 20
Non-legume hays	10 to 15
Corn, tobacco, and cotton stalks	8 to 10
Fresh green legumes	5 to 10
Cereal straws	5 to 6
Fresh, green, pasture grasses	4 to 8
Corn and other silages	3 to 6
Green vegetables and plant tops	2 to 5
Roots, tubers, and bulbs	2 to 4
Fruits	½ to 2

THE SOLUTION OF THE NITROGEN PROBLEM

The solution of the nitrogen problem lies in the conservation of the nitrogen compounds of the soil through the prevention of drainage losses, in the return of the nitrogen contained in the manure of the animals which are fed on the crops that are grown, in taking advantage of the nitrogen-fixing capacities of the symbiotic and non-symbiotic bacteria in soils, and in such supplemental applications of commercial nitrogen as economic conditions may warrant. The very important part that is played by the nitrogen-fixing bacteria is apparent. It is especially necessary to take advantage of these agencies in those cropping systems in which the acre values of the crops are not such as will allow for meeting the nitrogen requirements by the use of fertilizers.

Under favorable conditions, nitrogen fixation is quite rapid and is sufficient to satisfy the requirements of large yields of crops when grown in rotation with legumes, particularly if the legume crops are plowed under or are returned in the form of manure. The bacteria having to do with nitrogen fixation are benefited by most of the practices that are employed to increase the yields of ordinary crop plants. The application of limestone, the use of potash and phosphate fertilizers, the plowing under of organic matter, the installation of systems of tile drainage, and the plowing and cultivating of the soil are known to be effective in increasing the yields of ordinary crop plants. Undoubtedly, part of their effectiveness lies in their stimulating influence on the processes of nitrogen fixation in the soil.

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CHAPTER XVI

MINERAL ECONOMY IN SOILS

Of the inorganic elements that make up the mineral matter in soils, calcium, magnesium, potassium, phosphorus, and sulfur have received the most attention, primarily because of the relatively large amounts of them that are required by plants. The other essential mineral elements are usually present in such large amounts in soils, or they are used in such small quantities by plants, as to make their conservation a matter of relatively little importance. Such elements as iron, aluminum, and manganese are of considerable interest in relation to the growing of plants, but they can usually be kept from being limiting factors, whether by reason of excess or deficiency, by controlling the reaction of the soil.

However, in proportion as the period of time during which the land of the United States has been under cultivation has lengthened, there is increasing evidence that more attention will have to be paid to what are known as the trace elements. Previously, these trace elements were of interest only because of the necessity of supplying them when plants were grown in culture solutions. They did not enter into the problem of plant production in the field. Now they present a particularly difficult problem in practice because of the uncertainty about the extent of their deficiency.

CONTENT OF ESSENTIAL MINERAL ELEMENTS IN SOILS

Considering only those elements that are commonly supplied to the soil in the form of limestone and fertilizers, it is interesting to note the quantities of these that are present in the various types of soils and subsoils. Table 82 gives the number of pounds of each of these elements, calculated as their oxides, in 2 million pounds of each of 20 important soil types, and indicates the relative amounts of these elements in their respective subsoils. What might be considered an average soil of the humid area of the United States contains approximately 15,000 pounds of lime (CaO), 10,000 pounds of magnesia (MgO), 35,000 pounds of potash (K_2O), and 3000 pounds each of phosphoric and sulfuric acids (P_2O_5 and SO_3) in the surface acre of soil to plow depth, with additional amounts in the subsoil.

TABLE 82

POUNDS OF NUTRIENT OXIDES IN 2 MILLION POUNDS OF SOIL (ROBINSON)

Series	State	Depth, Inches	CaO	MgO	K_2O	P_2O_5	SO_3
Norfolk[1]	S. C.	8	3,800	200*	1,600*	2000	1600
Colorado[1]	Col.	14	18,800*	14,400	46,200*	2200	1400*
Ruston[2]	La.	6	2,400*	0*	3,200*	800*	4600
Durham[2]	N. C.	10	17,800	3,800	79,200	2400*	1200*
Cahaba[2]	Ga.	12	4,200	1,800*	18,000*	1200	1200
Sassafras[3]	Md.	8	8,200	7,200*	37,400*	3000*	1000
Clermont[3]	Ohio	6	15,400	19,000*	36,800*	3000	....
Marshall[3]	Mo.	15	21,600*	15,400*	45,600	4400	3400
Memphis[3]	Miss.	6	6,200*	7,800*	35,600*	1600*	600
Volusia[3]	N. Y.	8	9,800	9,600	28,000*	3600	1800*
Wabash[3]	Neb.	15	21,400	18,600	47,000*	2800	3200
Clarkesville[3]	Ky.	10	5,800*	4,600*	27,200*	1600*	1600*
Oswego[3]	Kan.	14	21,800	7,200*	45,600*	2000	2400*
Louisa[4]	Va.	12	4,200*	5,000*	14,800*	2400*	3000*
Carrington[4]	Iowa	12	16,800	11,200	27,000*	2800	2000
Hagerstown[4]	Pa.	8	18,600	21,600*	54,200*	3800	6800
Gloucester[4]	N. H.	8	27,200	16,600	43,200*	3000	3400
Miami[5]	Ind.	10	12,200*	12,400*	43,000*	5800	600*
Decatur[5]	Ala.	4	12,600	7,800	13,400*	3600	2600*
Stockton[6]	Cal.	38	46,800*	36,200*	15,600	4600	1200

* In these series the percentage content of the oxide in the subsoil was equal to or higher than in the surface soil.

[1] Sands. [2] Sandy loams. [3] Silt loams. [4] Loams. [5] Clay loams. [6] Clay.

The total amounts of the mineral nutrients that are contained in the soil and subsoil, in the depth to which roots penetrate, are very large. However, most of this supply is present in the form of primary minerals that are well covered by a protective coating of colloidal clay or humus. Yet, as the part which is present in the exchange form is used by plants, some of that in the primary minerals diffuses out into the exchange complex to take its place. This explains why " worn-out " soils recover their productivity if allowed to grow to weeds.

AGENCIES EFFECTING THE RENEWAL OF SURFACE SOILS

Liebig's mineral theory states that the crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substance conveyed to it in manures. The purpose of this statement and of Liebig's accompanying explanatory discussion was to call attention to the difference between the problem of the economy of nitrogen in soils and that of the mineral nutrients. It was Liebig's belief that the air is the source of the nitrogen of plants, while the inorganic elements can only be secured from the soil. Subsequent investigations have shown that his conception of the problem was essentially correct, although the method by which the nitrogen is accumulated is not that which he had conceived.

Whitney, in considering the application of this theory to American teachings and practices, came to the conclusion that it was being interpreted too literally. Large numbers of analyses of soils and plants for their total contents of these mineral nutrients had been and were being made, as a means of estimating both the present productive capacities of soils and also the rate at which these nutrient elements were being removed from them. The general assumption seemed to be that the soil was comparable to a bank account. On this basis, the original inventory by chemical analysis for total constituents gives the "account" against which "checks" are drawn by crop removal and drainage losses. In proportion as crops are grown and removed or losses of the mineral nutrients in the drainage water take place, additional "deposits" must be made in the form of manure or fertilizers.

Such a point of view neglects to take into consideration certain compensatory processes which tend, under good management, to effect a renewal of the surface soil. Among these processes, Whitney men-

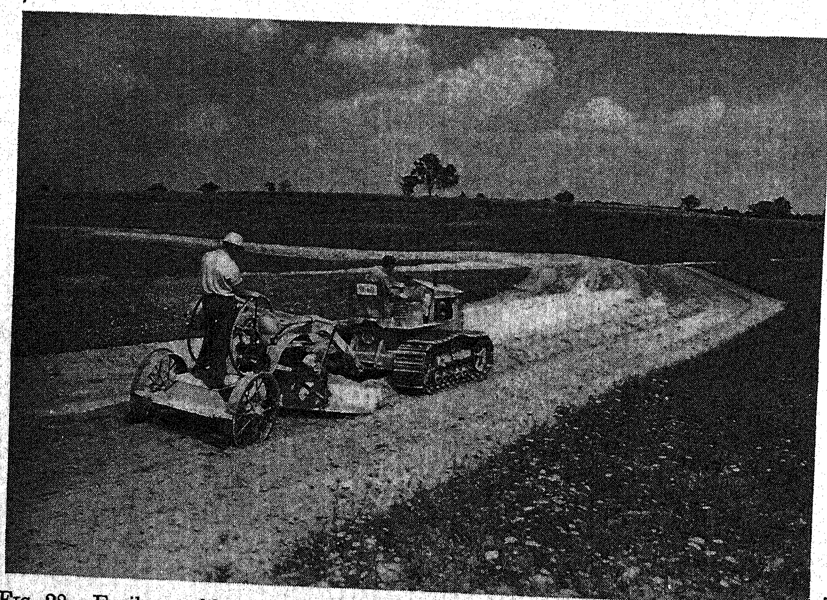

FIG. 28. Easily erodible soils, on the longer slopes, may require terracing to be held in place.

tioned the contributions of the atmosphere, the upward movement of soluble salts in plants and in capillary water, the action of burrowing worms and insects, and the effects of wind and water erosion.

THE ATMOSPHERE AS A SOURCE OF MINERAL NUTRIENTS

Early analyses of rainwater had to do largely with its content of combined nitrogen and chlorine. Subsequently, it was shown that the rain also contributes significant amounts of combined sulfur, potassium, calcium, sodium, and other mineral elements to the soil. Some of these have their origin in sea water and others in the smoke and gases emanating from flues and from the craters of volcanoes. These are condensed and brought to the earth in rain. The solid particles serve as nuclei around which drops of rain form. The total amount of these various materials that is contributed to a soil by this means is likely to be quite variable, depending on the location of the soil with reference to the sources from which the materials are derived.

While gases and solid particles may be carried considerable distances by the atmosphere before they are deposited on the soil, yet the nearer the land lies to the source of origin of these materials, the larger the amounts of them that are contributed to the soil. Thus, marked injury to vegetation has been noted in the vicinity of cement plants as a result of the large amounts of soluble potash in the dust that is deposited on nearby vegetation. Similarly, a large part of the plant life has been destroyed over large areas of land surrounding smelters in which sulfide ores were being roasted. But clover is benefited by dust from limestone roads.

The average annual acre contribution of sodium chloride is estimated at 24 pounds an acre at Rothamsted, England. The sulfur content of the rainwater at Urbana, Illinois, was found to be 40 to 50 pounds an acre, annually. Similarly, it has been shown that appreciable amounts of salts of potassium, magnesium, calcium, and other elements are added to the soil each year. While certain of the gaseous by-products of the various manufacturing processes are now being saved and used for fertilizer and other purposes, enormous amounts of smoke and gas are being poured into the atmosphere every day. These make important contributions to the soil of certain elements that are essential to plants, of some elements that are of little or no value to plants, and of others that have very injurious effects.

PLANTS AS SOIL-RENEWING AGENTS

It has been demonstrated that certain groups of soil bacteria are able to accumulate atmospheric nitrogen. Similarly, plants secure their carbon from the air and leave it behind in their residues in the soil. No such process of accumulation is possible for the inorganic nutrients. The quantity of them that may be present in the air, in the form of finely divided particles, is quite small. The only means by which a plant may effect an increase in the mineral content of the soil is through the agency of its root system, which serves as a medium for the transfer of mineral elements from the subsoil to the surface soil.

That such a translocation takes place is indicated by the fact that most surface soils contain a little more phosphorus than do their subsoils. While this fact may have some other explanation, it seems reasonable to believe that such a process is in operation in the plant, and that any soluble nutrient in the subsoil which comes into contact with a root hair may be absorbed and carried to the higher portion of the roots or to the above-ground portion of the plant. Weeds probably perform an important function in renewing the mineral content of the surface soil at the expense of the subsoil. The good effects that result from plowing under a luxuriant crop of sweet clover may be due not only to the nitrogen that its nodule bacteria have accumulated from the air, but also to the mineral contribution that is made to the surface soil as a result of the large spread of roots which is produced by this plant.

CAPILLARY MOVEMENT OF SOLUBLE SALTS

The rate of diffusion of soluble salts in soils is slow. These salts may be carried upward by capillary water, or by gravitational water accompanying a rise in the water table. In diffusion of this sort there will be an accumulation of salts on the surface of the soil unless the upward capillary movement is balanced by a downward gravitational movement. The alkali deposits that cause so much trouble in the semi-arid regions have their explanation in this fact. However, if a solution of soluble salts is placed at the bottom of a column of soil, the various ions do not move upward with equal facility because the soil exercises certain selective adsorption effects that retard the movement of some ions much more than that of others. This is shown in the data in Table 83, which were secured by supplying a water solution of salts at the base of 24-inch columns of soil, exposing their surfaces to the action of evaporation, and determining the salt content at various depths of these columns at the expiration of periods of from seventeen to twenty days. Additional water was supplied at the bottom of the soil columns to take the place of what was lost from the surface by evaporation.

It is apparent that the calcium and nitrate ions are much more readily moveable in the soil than are the others. In the phosphate ion, very little change in concentration is to be noted in the various depths of the soil column. This indicates that the soil has a very marked capacity to adsorb this ion from solution.

TABLE 83

EFFECT OF CAPILLARY MOVEMENT ON DISTRIBUTION OF IONS IN SOILS (KING)

Soil Type	Concentrations in Parts per Million					
	K	Ca	Mg	NO_3	HPO_4	SO_4
Norfolk Sand:						
0–1 inch below surface	31	300	63	1068	4.8	34
10–12 inches below surface	8	26	10	43	4.3	36
Original soil	15	15	11	46	3.7	40
Selma Silt Loam:						
0–1 inch below surface	65	2125	273	3632	3.3	375
10–12 inches below surface	10	90	11	58	7.1	175
Original soil	16	450	15	201	4.9	95
Hagerstown Clay Loam:						
0–1 inch below surface	28	550	155	1730	9.3	168
10–12 inches below surface	15	108	41	145	10.3	228
Original soil	13	116	33	234	9.9	75
Solution supplied*	119	30	41	55	49.9	162

* Solutions of salts supplied at bottom of 24-inch columns of soil.

EFFECT OF EARTHWORMS ON SOILS

It has been repeatedly observed that various species of burrowing forms of animal life tend to effect a translocation of the subsoil to the surface. Of these, perhaps the one that is most generally distributed is the earthworm. It inhabits practically all soils that contain suitable amounts of lime and organic materials. It has been shown that the number of earthworms in the soil may be quite large, amounting to more than a million in an acre. If some of these worms are confined in a jar of soil, it is found that they multiply quite rapidly under suitable conditions and that their casts soon cover the surface of the soil to a considerable depth. Undoubtedly earthworms effect some change in the soil as it passes through their bodies, in that they digest the organic matter, with the resulting formation of excretory products, of which calcium carbonate is known to be one.

The extent to which earthworms bring up the subsoil and deposit it on the surface is unknown; but Darwin, in a very interesting discussion of the subject, attributed to them a translocation of soil amounting to 1 inch in 5 years. This conclusion is based on observations as to the rate at which such materials as stones, which were supplied to the surface, became embedded in the soil. The burial of the ruins of ancient cities was credited by Darwin to the action of earthworms. According to his estimate, as much as 10 tons of material annually passes through the bodies of the earthworms in an acre of soil in certain parts of England. As the weather becomes dry, earthworms tend to penetrate to greater depths in the soil, but apparently they continue to return to the surface to deposit their casts and thereby effect a renewal of the surface soil at the expense of the subsoil.

EROSION AS A FACTOR IN SOIL RENEWAL

The action of wind and of running water is such as to effect a translocation of the surface soil, with the result that it is deepened in some localities whereas subsoil is brought to the surface in others. In either case, the effect may be a complete renewal of the soil, so that the farmer of one generation may be dealing with entirely different soil from that with which his predecessor worked. In areas in which wind erosion operates most effectively, the transfer of soil may be so rapid as to cover the existing soil to a depth of several inches in a few hours' time. This is a common experience in those areas that are covered with sand or muck.

FIG. 29. An area of 1,903,000,000 acres of land that must be conserved.

The most extensive erosion, although somewhat less rapid, is that which is caused by running water. This is particularly effective on rolling land that is frequently cultivated. The rate at which the surface soil is removed is determined by the character of the soil, the frequency with which cultivated crops are grown, the climatic conditions, as to both rainfall and temperature, and the slope of the land. Geologists estimate that the land is being eroded by water at a rate of 1 inch for every 200 to 500 years. The average rate at which the United States is being denuded is believed to be 1 inch in 760 years. Land that is under cultivation, even though it has only a moderate slope, may be expected to be eroded at a rate of an inch or more a century under climatic conditions such as obtain in the humid regions of the United States.

The result of an investigation on the rate of erosion under field conditions is given in Table 84. The soil is a Shelby loam with a fall of 3.68 feet to 100 feet. The average annual rainfall amounts to 36 inches. The greatest damage was done by the occasional torrential rain, particularly if it fell when the soil had recently been cultivated and was bare of vegetation.

TABLE 84

Annual Rate of Removal of Soil by Water Erosion (Duley)

Soil Treatment	Tons of Soil Removed per Acre	Years Required to Remove 7 Inches	Percentage Rainfall Run-off
Uncultivated, weeds pulled	207	29	49
Cultivated throughout summer	247	24	31
Same with deeper plowing	214	28	28
Continuous sod	2	3547	12
Wheat every year	40	150	25
Corn, wheat, and clover	14	437	14
Corn every year	107	56	27

DRAINAGE LOSSES OF MINERAL NUTRIENTS

In semi-arid regions, the upward movement of soluble salts in the capillary water is such that surface accumulations in the form of alkali result. In humid regions this upward movement is likely to be more than overcome by the losses which occur in the drainage water. That these losses are considerable is evidenced by the acid reaction of the soils of humid regions and the accumulation of salts in the ocean. Of interest in this connection are the analyses of river waters. The following table gives the salt content of water taken from the Mississippi River at various points along its course.

TABLE 85

PERCENTAGE COMPOSITION OF SALT CONTENT OF RIVER WATERS (CLARKE)

	A*	B	C	D	E	F	G	H
CO_3	51.65	48.03	42.27	43.15	33.23	30.23	30.27	34.98
SO_4	1.05	9.35	13.58	12.55	21.74	20.50	19.69	15.37
Cl	.48	.83	2.09	2.21	3.79	4.10	11.05	6.21
NO_3	.....	.73	1.01	1.10	1.05	.81	.....	1.60
PO_4	.....	.....	.....	.....	.....	.....	.27	.....
Ca	22.94	20.77	18 68	18.06	17.08	17.16	20.25	20.50
Mg	4.09	7.27	7.35	8.03	6.22	5.72	4.66	5.38
Na	5.14	†	†	†	†	8.09	6.86	†
K	1.75	5.19	5.65	5.52	8.15	1.52	1.57	8.33
SiO_2	9.40	7.78	9.09	9.03	8.54	11.44	5.07	7.05
Al_2O_3	2.01	.....	.....	.....	.....	.....	.12	.45
Fe_2O_3	1.49	.05	.28	.35	.20	.43	.08	.13
Mn_3O_4	.....	.....	.....	.....	.....	.....	.11	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Salinity, p.p.m.	195	200	179	203	269	202	146	166

* A = Brainerd, Minn. B = Minneapolis, Minn. C = Moline, Ill. D = Quincy, Ill. E = Chester, Ill. F = Memphis, Tenn. G = Carrolton, La. H = New Orleans, La.

† Na included with K.

It is evident that the concentrations of the chlorides and sufates increase as the water continues on its way to the Gulf of Mexico. Two explanations can be given for this. One lies in the contamination

TABLE 86

COMPOSITION OF SOIL DRAINAGE WATER IN PARTS PER MILLION (VOELCKER)

Treatment	CaO	MgO	K_2O	Na_2O	SO_3	P_2O_5	N*
None	98	5.1	1.7	6.0	25	0.6	4
N	154	7.4	1.9	7.1	44	1.4	14
N, P	166	7.3	1.0	6.6	54	1.7	15
N, P, Na	192	6.6	2.7	24.6	97	1.3	15
N, P, K	201	9.3	3.3	6.1	87	1.1	18
N, P, Mg	227	11.6	1.0	5.6	100	1.0	19
N, P, Na, K, Mg	181	8.3	2.9	10.9	90	0.9	14
P, Na, K, Mg	124	6.4	5.4	11.7	66	0.9	5

N = 106 pounds of the element from equal amounts of sulfate and chloride of ammonia. P = 66 pounds of P_2O_5 as superphosphate. K = 96 pounds of K_2O as the sulfate. Na and Mg = 100 pounds of each of the sulfates of these elements. These amounts are calculated on the acre basis and are supplied annually.

* Practically all this nitrogen was present as a nitrate.

of the water with sewage. The other is found in the contributions made by rivers, such as the Missouri, that have their origin in areas of alkali soils.

Of particular interest from the point of view of field economy of the mineral nutrients are the data from the Broadbalk field at Rothamsted. Each plot on this field is underlain by a tile drain, whose water can be collected at the end of the field where an excavation has been made for this purpose. Several analyses have been made of water from these tile, the averages of which are recorded in Table 86.

ADSORPTION BY SOILS

The losses of the soluble constituents from soils vary with the nature of the soil, the fertilizer and manurial treatments, the cropping system, and the amount of rainfall and drainage. The soil on Broadbalk field is a heavy clay filled with fragments of chert. Wheat is being grown continuously on this field. The average annual rainfall at Rothamsted is 28.75 inches, of which approximately one-half is estimated to percolate through the soil and to run out the end of the tile. The above data are of value for purposes of comparison of the losses of the various elements. They give some idea of the capacity of the soil to adsorb the phosphate, potassium, and ammonium ions and of the soil's inability to retain the calcium, sulfate, and nitrate ions.

This selective capacity of soils whereby certain ions are prevented from moving through the soil with the drainage water, while others are not, has been the subject of an enormous amount of investigation. It is now known that phosphates are fixed by the soil, either by becoming a part of the colloidal complex or by precipitation as iron, aluminum, or calcium phosphates, depending upon the soil reaction. In the calcium, magnesium, potassium, and ammonium ions, the phenomenon is one of exchange in which these ions are substituted for other cations already present in what is known as the exchange complex of the soil.

EXCHANGE COMPLEX OF SOILS

The colloidal matter of soils has been found to be composed largely of aluminosilicates which have definite capacities to adsorb cations. The ratios of the several cations which are attached to this exchange complex vary with the conditions under which the soil was formed. These ratios can be altered by liming and fertilizer treatments. For normal use, the soil is in best condition for growing plants when the cations in the exchange complex consist largely of calcium, with fair amounts of magnesium and somewhat smaller amounts of potassium and sodium. In proportion as the soil becomes acid in reaction, hydrogen is substituted for the other cations in the complex, and productivity normally decreases.

If the soil is leached with water containing a soluble salt, a replacement is effected between the cation of that salt and the cations in the exchange complex. If the soil is well supplied with calcium, the normal effect of the leaching process is to replace this calcium which is then carried to lower depths in the soil. It may be lost in the drainage water.

Exchange reactions occur only in soils which contain colloidal clay or organic matter. Sands have little exchange capacity because they are made up largely of quartz grains, and contain little colloidal material. It is, therefore, not possible to store up any considerable amounts of the nutrient elements in sandy soils. In contrast, the more or less permanent productivity of the clay-loam types of soil depends upon their high content of colloidal matter and the exchangeable cations associated with it. When such soils are treated with lime, the applied calcium and magnesum effect an exchange with the hydrogen in the complex. When fertilizers are applied, their cations replace some of the calcium previously supplied by the liming material.

Plant physiologists have determined the ratios in which the several nutrient cations must be present in solution cultures for optimum growth of plants. However, if such nutrient solutions are applied to a soil, exchange reactions take place, as a result of which the ratios of the several ions are greatly changed. There is great need to study the means by which the findings of the plant physiologists can be put to field use.

The chemical analysis of a soil for its total constituents gives little information concerning the form in which the various elements exist in the soil. The several base-forming elements may exist in the form of undecomposed mineral particles, as simple amorphous salts, or loosely combined with the colloidal complex of the soil in such condition as will permit of their being displaced by treatment of the soil with salt solutions. They may be available for plant use, no matter whether they are present in the soil in one or the other form, but the processes by which they become available differ, depending upon the nature of the compound in which they exist.

MINERAL NUTRIENTS REMOVED BY CROPS

While the analysis of a plant does not necessarily provide exact information as to its mineral requirements, it does permit of our knowing how much of each element was taken from the field when the crop was harvested and removed. Plants differ considerably in their percentage content of the several elements, depending upon the species, the variety, the nature of the soil on which they were grown, and the weather conditions under which their growth took place. While plants of the same species when grown under the same conditions are quite similar in composition, yet it is well to keep in mind that, in the event of an excess of any element, the percentage of that element in the plant may be quite high, and that the opposite may be true in case of a deficiency. Table 87 gives the approximate content of mineral nutrients of the various groups of crops or of the portions of them that are harvested.

TABLE 87

Pounds of Nitrogen and Mineral Nutrients per Acre of Crop (Forbes)

Crop	Yield	N	K_2O	CaO	MgO	SO_3	P_2O_5
Corn	100 bu.	78	23	1	10	21	33
Oats	100 bu.	58	16	5	6	16	29
Wheat	50 bu.	50	19	2	7	15	26
Soybeans	25 bu.	95	34	4	6	15	20
Corn stover	2½ tons	44	103	33	7	22	11
Wheat straw	2½ tons	14	48	13	5	19	4
Clover hay	3 tons	125	122	96	27	26	23
Timothy hay	3 tons	51	40	14	10	22	16
Apples	400 bu.	10	34	1	2	4	3
Potatoes	400 bu.	77	78	2	2	15	26
Onions	400 bu.	63	53	11	7	46	23
Cabbage	10 tons	38	42	11	5	32	8
Mangels	20 tons	108	213	8	28	26	28

THE ECONOMY OF MINERAL NUTRIENTS

The conception of the soil as a bank account on which checks are drawn and to which deposits are made is not strictly applicable. Soils are dynamic. Their particles are moved from place to place through the action of water, winds, and living things, of which plants and earthworms are particularly important in their effects. Meanwhile, the soil continues to undergo disintegration and decomposition processes; besides, the soil is subject to losses through crop removal and through leaching by drainage waters.

Nevertheless, it seems logical to take all these agencies into consideration and to use such means to regulate their effects as will best economize on the resources of the soil. In time, supplemental treatment of the soil with liming and fertilizer materials becomes necessary.

But the need for these materials can be delayed and reduced to a very considerable extent by giving consideration to the possibilities of conserving the mineral nutrients now in the soil.

It is good business to utilize the resources of the soil to the fullest possible extent by giving adequate attention to cultivation, drainage, the plowing under of organic matter, and the growing of deep-rooted crops. Many opportunities are presented for reducing the waste of mineral nutrients by stopping soil erosion, by preventing leaching losses from manure, by keeping the soil covered with vegetation to prevent the loss of nutrients in the drainage water, and by transferring mineral elements from the subsoil to the surface through the medium of the roots of soil-rejuvenating plants.

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CHAPTER XVII

LIMESTONE ECONOMY IN SOILS

In humid regions, the problem of maintaining the reaction of the soil at a point that is suited to the needs of crops is one that requires considerable attention. As the basic constituents are removed in the drainage water and in crops, the reaction of the soil becomes more and more acid, until a point of equilibrium is finally reached at which no further increase in intensity of acidity takes place. It is seldom that the reaction of the soil falls much below *p*H 4.5 under most systems of management. Ordinarily, the soil does not become so acid but that a number of the less sensitive crops can still be grown satisfactorily without the use of liming materials. One has the choice, therefore, between growing acid-tolerant crops, to which very little lime need be applied, and producing the more sensitive crops for which it may be necessary to maintain the soil reaction at a point approaching neutrality.

In the more specialized types of farming, considerations of economy are ordinarily set aside, and limestone, if needed, is applied in liberal quantities. In localities that are somewhat far removed from the source of supply of liming materials, and for crops whose acre values are relatively low, quite the opposite plan is often followed. In the latter case, it may be desirable to adopt a policy of compromise in which consideration is given to the choosing of crops that are somewhat tolerant of acid soil conditions, to means by which the loss of basic constituents from the soil may be reduced, to methods other than liming which may aid in controlling the reaction of the soil, and to using only such amounts of liming materials as may actually be required.

SENSITIVENESS OF PLANTS TO ACID SOIL CONDITIONS

It is a well-known fact that such crops as alsike clover, rye, potatoes, carrots, and cucumbers will produce satisfactory yields on soils that are too acid for alfalfa, barley, cabbage, spinach, or muskmelons. The explanation is to be found in the inherent differences in the physiology of plants. Enough is known concerning the problem to permit of the conclusion that, in some cases, the difficulty with acid soils lies in a deficiency in available forms of one or more of the nutrient elements required by plants, while in other cases it is due to the presence, in toxic concentrations, of elements that have no nutritive value. The effect on the plant may be either direct or indirect. Among the indirect effects may be mentioned the influence of the reaction on the microbiological activities in soils.

From the experimental data that are now available on this subject, it is possible to arrange many of the crop plants in the order of their sensitiveness to acid soil conditions. Thus, at the Rhode Island Experiment Station, 280 different varieties of plants have been grown in comparative tests on limed and unlimed soils, and the effects of the liming treatment have been noted. From these experiments and others of a similar nature, Table 88 has been arranged to indicate the choice which one may have in the selection of plants to fit the reaction of the soil.

TABLE 88

RELATIVE SENSITIVENESS OF PLANTS TO ACID SOIL CONDITIONS

Very Tolerant	Tolerant	Sensitive	Very Sensitive
Beans	Alsike clover	Barley	Alfalfa
Bent grass	Buckwheat	Bluegrass	Asparagus
Blackberry	Carrot	Brussels sprouts	Beet (red)
Blueberry*	Corn	Cabbage	Beet (sugar)
Cowpea	Cotton	Cauliflower	Berseem clover
Cranberry*	Crimson clover	Chard	Bokhara clover
Fescue (sheep's)	Cucumber	Egg plant	Celery
Flax	Endive	Hemp	Currant
Japan clover	Gooseberry	Horseradish	Gumbo (okra)
Lupine	Grape	Muskmelon	Leek†
Millet	Lentil	Mustard	Lettuce†
Oats	Pea	Orchard grass	Mangel
Peanut*	Pumpkin	Rape	Onion†
Potato	Rhubarb	Red clover	Parsnip
Radish	Raspberry (red)	Sweet clover	Pepper
Raspberry (black)	Strawberry	Turnip	Quince
Red top	Tomato	Tobacco	Salsify
Rye	Timothy	Wheat	Spinach†
Watermelon*	Vetch	White clover	Yellow trefoil

* Especially tolerant of acid soil conditions.
† Especially sensitive to soluble aluminum.

LOSSES OF BASIC OXIDES IN DRAINAGE WATERS

The rate at which the base-forming elements are leached from the soil is determined by the nature of the minerals supplying them, the total exchange capacity of the soil, the amount of water which percolates through it, and the system of cropping that is being followed.

One of the most interesting tests of such losses is that reported from Cornell in lysimeter experiments with two quite different types of soils. The lysimeter tanks contain 4-foot depths of soil in which the various horizons are placed in the order in which they existed in the natural state. The soils and subsoils are all acid in reaction except the fourth foot of the Dunkirk clay loam, which contained sufficient carbonates to yield 2.68 per cent carbon dioxide at the beginning of the test. The following data are averages for five-year periods and are calculated on the acre basis.

TABLE 89

ANNUAL ACRE LOSS OF BASIC OXIDES IN DRAINAGE WATERS (LYON)

	Dunkirk Clay Loam			Volusia Silt Loam		
	Soil, first foot, per cent	In Drainage Water		Soil, first foot, per cent	In drainage water	
		Cropped, pounds	Bare, pounds		Cropped, pounds	Bare, pounds
CaO	0.34*	248	519	0.23*	361	447
MgO	0.35*	57	102	0.56	51	70
K_2O	1.83*	56	88	1.69*	107	119
Na_2O	0.86	113	165	1.12	138	149
Drainage in inches		18	26		21	29

* In each of these cases the content of the oxides tended to increase with the depth.

The losses recorded in Table 89 are probably much larger than would have occurred with the same soil under field conditions and under the same climatic environment. The data, therefore, should be considered as being relative rather than absolute.

With the exception of potassium, each of the above elements is contained in considerably larger amounts in the drainage water than in the crops that are removed. Thus, in the case of the Dunkirk clay-loam soil, the average annual acre losses in the harvested crops were 21, 12, 95, and 11 pounds each of the oxides of calcium, magnesium, potassium, and sodium, respectively. Cropping the soil reduces the losses of all of the basic oxides, particularly those of calcium and magnesium. It is thus apparent that one of the methods which may be used to economize in the losses of basic constituents from soils is that of keeping the soil covered with vegetation as much of the time as possible. The saving is largely that resulting from substituting transpiration for drainage as a means of removing water from soils.

THE VALUE OF THE CALCIUM IN FERTILIZER SALTS

Investigational work indicates that the most productive soils contain relatively large amounts of calcium in easily replaceable or readily soluble forms. Its presence in the carbonate form is desirable for those plants that are especially sensitive to acid soil conditions. For the less sensitive plants, it is possible that the calcium requirements of the soil and crop may be satisfied by the quantities of this element that are added to the soil in the form of fertilizer salts. All the ordinary phosphate fertilizers carry calcium as the phosphate. In superphosphate, part of this has been changed to the sulfate form. Calcium sulfate once enjoyed considerable popularity as a fertilizer, and may be responsible in part for the good effects usually noted as a result of the use of superphosphate.

The amount of replaceable calcium in soils is not determined by the soils' *p*H, but by the the soils' exchange capacity. This is very well shown in Table 90, in which the *p*H values of the various soils are recorded, together with the amount of calcium these soils contained that could readily be replaced when the soils were washed with a solution of ammonium chloride.

The immediate effect of adding a soluble salt of calcium, such as the sulfate or chloride, to acid soils is to increase the acidity since the calcium ions are substituted in the exchange complex for hydrogen ions which, in turn, are released to the soil solution and move more deeply into the subsoil. If a deficiency of calcium is a limiting factor in the growth of the crop and if the increased acidity of the soil solution is not

TABLE 90

REPLACEABLE CALCIUM CONTENT OF VARIOUS ACID SOILS (KELLEY)

Type	Location	*p*H	Ca*
Miami loam	Michigan	6.59	0.219
Cecil clay loam	Georgia	6.12	0.018
Gloucester silt loam	Wisconsin	5.90	0.169
Tidal marsh clay loam	California	5.73	0.112
Volusia silt loam	New York	5.22	0.103
Clermont silt loam	Indiana	5.14	0.068
Greenville sandy loam	Alabama	5.10	0.041
Rhonesville clay loam	California	5.05	0.053
Melbourne clay loam	Oregon	4.99	0.037
Holston silt loam	Alabama	4.97	0.056
Greenville clay loam	South Carolina	4.80	0.060
Hagerstown clay loam	Pennsylvania	4.77	0.021

* As percentage of dry weight of soil.

harmful, then the use of calcium in other than carbonate forms may be effective in increasing crop yields. Furthermore, if the physical nature of the soil is such that drainage water passes through it readily, a complete exchange of the calcium in the added salt for hydrogen in the soil may gradually be effected without increasing the acidity of the soil at any time to a point that is injurious to the crop. This is a partial explanation for the increased crop growth which frequently results from the liberal use of landplaster as a soil amendment. It may also account for the good effects that have been noted from the use of common salt on sandy loam soils in regions of heavy rainfall.

EFFECT OF FERTILIZER SALTS ON THE SOIL REACTION

It is possible to exercise some selection in the use of fertilizer materials as related to their effects on the soil reaction. The comparative effects of nitrate of soda and sulfate of ammonia have often been noted in this connection. Basic slag is a well-known carrier of phosphoric acid and also contains a considerable percentage of calcium in an alkaline form. Contrary to the usual impression, superphosphate does not appear to increase the acidity of the soil even when used in liberal amounts. The relative effects of the various groups of fertilizer materials on the soil reaction is shown in the accompanying table, giving the results of tests for active acidity, made during the summer of 1921, on soil that had been under experiment with fertilizers since 1898.

TABLE 91

EFFECT OF FERTILIZER SALTS ON THE SOIL REACTION* (BURGESS)

Carriers of Nitrogen		Carriers of Phosphorus		Carriers of Potassium	
MATERIAL	pH	MATERIAL	pH	MATERIAL	pH
Nitrate of soda	6.3	Basic slag	5.87	Kainit	6.53
Hen manure	6.0	Bone meal	5.70	Extra sulfate	6.45
Dried blood	5.8	Phosphate rock	5.65	Sulfate of potash	6.40
Tankage	5.8	Superphosphate	5.52	Manure salts	6.40
Sulfate of ammonia	5.7*	Superphosphate†	5.52	Muriate of potash	6.30
None	6.1	None	5.41	None	6.06

* In these tests, covering considerable periods of time, the soil received relatively small amounts of lime and other fertilizer materials. The data for each fertilizer element are comparable, with the exception of the case of sulfate of ammonia, where a calculation was necessary from other data that were available.

† Made by treating phosphate rock with phosphoric acid.

From the above data, it is evident that the net effect of the use of fertilizers, other than most of the carriers of nitrogen, is to decrease the effective acidity of the soil. The fertilizer applications were not particularly heavy. With an increase in the rate of application of phosphate and potash salts or of nitrate of soda, still more favorable effects on the soil reaction would have been observed. The soil on which these tests are being conducted is a silt loam of granitic origin which is normally very acid in reaction, having a *p*H of about 4.5 and containing only 0.02 per cent of calcium oxide that is extractable with carbonated water.

IMPROVING THE BUFFER QUALITIES OF SOILS

A solution is said to be highly buffered when it will absorb relatively large amounts of acid or alkali without effecting a marked change in its hydrogen-ion concentration. If one titrates a tenth-normal solution of hydrochloric acid with a solution of sodium hydroxide of corresponding strength, a very sharp endpoint with an acid-alkali indicator is observed. This means that one drop of the alkali has caused a very marked change in the hydrogen-ion concentration of the solution. If some sodium acetate is added to the hydrochloric acid before the titration is made, the change in the color of the indicator is more gradual. The sodium acetate neither increases nor decreases the amount of neutralizable acid in the solution. Its use results in the formation of highly ionized sodium chloride and the weakly ionized acetic acid, and thereby reduces the hydrogen-ion concentration of the solution. A tenth-normal solution of hydrochloric acid has a normality, with respect to hydrogen ions, of 0.091 (*p*H 1.04). This is a concentration that is seventy times that of a tenth-normal solution of acetic acid, which therefore has a *p*H of 2.89.

In the laboratory, advantage of this fact is taken in the preparation of nutrient culture solutions when it is desired to control their hydrogen-ion concentrations within rather narrow limits. Plants tend to alter the reaction of the solution during their growth. Accordingly, phosphates are employed as buffering agents. The necessary amounts of the several cations and anions are then supplied in the form of their salts. A solution of sodium hydroxide or of hydrochloric acid is added until the *p*H is at the desired point. The growing of a plant in such a nutrient solution effects relatively little change in the *p*H of the solution, whether the plant absorbs more of its basic ions than of its acidic ions or vice versa.

A soil that contains considerable amounts of colloidal material having a high adsorptive capacity for basic ions, if it is saturated with respect to these ions, has a very marked buffer effect on any acid that may be added to it. Similarly, humus materials serve very effectively as buffering agents in soils. In fact, it has been shown that organic colloidal material is nearly ten times as effective as a buffer as is colloidal matter of inorganic origin. The opportunity for improving these qualities of soils lies quite largely in increasing the content of humus in them. This is one of the important reasons why florists and gardeners insist on the use of large amounts of well-decomposed manure, compost, and leaf mold in preparing the soil for plants that must be forced rapidly. The buffering qualities of such soils are of value, not only in controlling the reaction of the soil solution, but in regulating the supply of mineral nutrients as well.

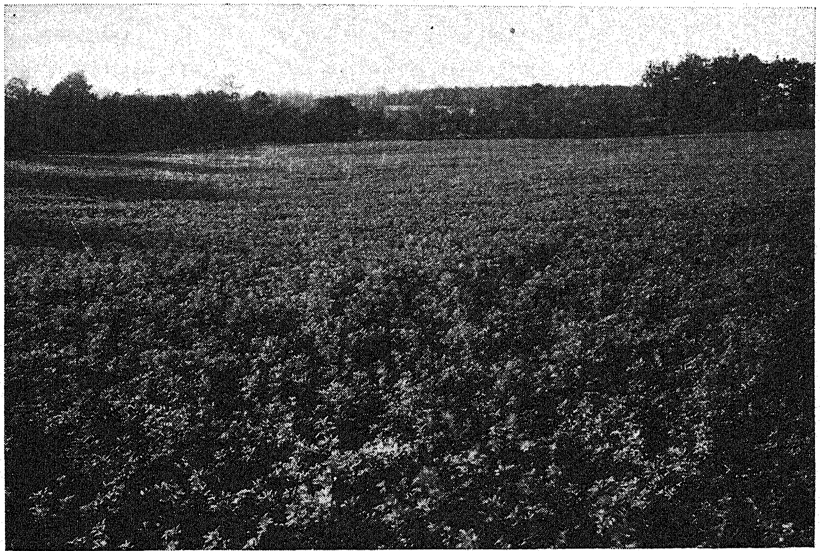

Fig. 30. The goal of every livestock farmer is the production of a good alfalfa crop. This plant thrives only on well-limed, well-drained, and highly fertile soils.

EFFECT OF DECAYING ORGANIC MATTER ON SOIL REACTION

Although it is desirable to have the soil contain relatively large amounts of humus, most organic materials that are plowed into the soil for that purpose contain larger amounts of acid than of base-forming elements, when calculated to their equivalents of some standard such as carbonate of lime. This is very well shown in Table 92, in which the calcium carbonate equivalents of the calcium, magnesium, sodium, and potassium of a few materials that are often incorporated with the soil are compared with those calculated from their content of nitrogen, sulfur, chlorine, and phosphorus. No consideration is given to the iron, aluminum, manganese, and silicon content of these materials.

The only one of the materials that yields an excess of base over acid is wheat straw. Ordinarily, the plants that contain the highest percentages of nitrogen are the ones that have the greatest excess of acid over base. Fortunately, the process of decomposition does not go on

TABLE 92

$CaCO_3$ EQUIVALENTS OF NITROGEN AND MINERAL NUTRIENTS OF PLANTS* (FORBES)

Materials	Base-forming Elements					Acid-forming Elements				
	K	Na	Ca	Mg	Totals	N	S	Cl	P	Totals
Clover hay	43.4	2.7	57.2	23.6	127	148.6	11.0	6.8	16.6	183
Soybean hay	40.6	5.6	61.6	50.0	158	194.2	15.0	2.2	20.8	232
Corn stover	43.8	2.6	23.6	7.0	77	62.6	10.8	8.0	9.4	91
Wheat straw	40.4	9.7	10.2	4.8	65	20.0	9.4	5.6	3.6	39
Timothy hay	14.4	13.8	8.8	8.2	45	61.0	9.4	5.2	11.2	87

* Calculated on the basis of pounds of $CaCO_3$ equivalents per ton of material.

to completion immediately, and the humus materials serve to buffer the effect of their own acid. Since crop plants contain more acid than base, all of them, except legumes, must absorb more acid than base from the soil. The net effect of plowing under crop residues to increase crop yields is to stock the soil with humus materials with their well-known buffering effect and to keep the elements of plant food in circulation.

THE RELATIVE LIME REQUIREMENTS OF PLANTS

The *lime requirement of a plant* has been defined as its need for lime as related to the ease and rate at which this lime must be secured from the soil by the plant for normal growth. According to Truog, the factors determining the lime requirement of a plant are its lime content, its rate of growth, and the extent and character of its root system. A plant with a high content of lime, a rapid rate of growth, or a relatively restricted root system would be said to have a high lime requirement. For a high-lime plant like alfalfa, for example, an abundance of lime in the soil is believed to be essential, even aside from its effect in relation to the reaction of the soil solution.

If the lime content of the plant, in relation to its lime requirement as above defined, were the only factor to be considered, then, in any attempt to economize in the liming program, plants might well be arranged in the rotation in such an order as to make one containing only small amounts of lime follow or precede one that is high in its content of this material. Thus, the data in Table 93 indicate that cabbage should be followed by beets rather than by carrots, whereas oats might well precede alfalfa. There is some evidence that the sequence of crops, when they are grown in rotation on acid soils, should take this factor into consideration.

TABLE 93

RELATIVE PERCENTAGES OF CALCIUM OXIDE IN PLANTS (FORBES)*

Class	Very High†		High	Medium	Low	Very Low
Vegetable leaves	Cabbage	(5.9)	Carrot	Turnip	Onion	Beet
Tree leaves	Mulberry	(5.1)	Grape	Chestnut	Oak	Pine
Vines	Pea	(3.1)	Potato	Hop	Sweet potato	Strawberry
Legume hays	Cowpea	(2.7)	Soybean	Alfalfa	Red clover	Alsike clover
Vegetables	Lettuce	(2.6)	Spinach	Celery	Cabbage	Onion
Roots and tubers	Radish	(1.4)	Turnip	Carrot	Potato	Sugar beet
Non-legume hays	Corn stover	(0.7)	Bluegrass	Millet	Wheat straw	Timothy
Legume seeds	Navy bean	(0.3)	Soybean	Cowpea	Sweet clover	Peanut
Cereal grains	Oats	(0.2)	Wheat	Corn	Kaffir	Rice
Fruits	Date	(0.1)	Prune	Strawberry	Apple	Cranberry

* The plants or parts of plants are arranged from top to bottom and from left to right in the descending order of the content of CaO. Thus the percentage of CaO in dry cabbage leaves is approximately 6 as compared to 3 for beet leaves, 0.1 for the date, and 0.03 for the cranberry. Some of the data for this table were taken from Truog's compilation.

† Percentages of CaO in the plants or parts of plants are given in this column.

ACID SOILS IN RELATION TO NITROGEN ECONOMY

The soil reaction is of particular interest in connection with the question of the accumulation of atmospheric nitrogen and the rate of nitrification in soils. The assumption is that those legumes which grow well on acid soils have an acid-tolerant type of nodule bacteria associated with them, and that these are able to function satisfactorily notwithstanding the acidity. However, if lime is applied, these legumes will usually grow much more luxuriantly and contain more pounds of nitrogen in an acre of produce. Most of the biological processes in the soil are speeded up by applying liming materials, as the data in Table 94 indicate.

The soil that was used in this test was Wooster silt loam, having a lime requirement, calculated according to the Veitch method, of about 4000 pounds. While the applications of limestone were effective in increasing the rate of ammonification, nitrification, and particularly nitrogen fixation, yet all these processes were being carried on in the unlimed soil. The fact that some plants not only grow well on quite acid soils but are actually injured as well by the use of liming materials indicates that at least some nitrogen is available for their use. For such crops, nitrogen fertilizers of an acid nature are often more effective than those that leave an alkaline residue.

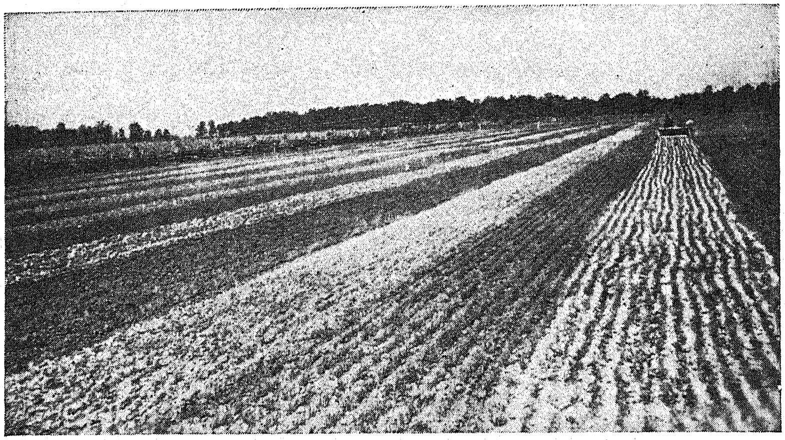

FIG. 31. Most farmers wait until the land is plowed before applying lime. But there is increasing need that more lime be applied before plowing. Often it would be better to "lime both sides of the furrow." By plowing lime under, conditions are made more favorable for deep rooting.

TABLE 94

SOIL REACTION AND EFFICIENCY* OF NITROGEN-CYCLE ORGANISMS (BEAR)

Limestone, Pounds per Acre	Ammonification of Casein	Nitrification of $(NH_4)_2CO_3$	Nitrogen Fixation, Non-symbiotic
0	57	50	16
250	52	53	30
500	55	56	30
1,000	60	57	38
2,000	82	77	32
3,000	86	83	94
4,000	100	100	100
5,000	113	125	106
7,500	100	109	132
10,000	112	107	83

* Percentage efficiency to that in neutral soil rated at 100.

THE SOLUTION OF THE PROBLEM OF LIMESTONE ECONOMY

If for any reason it may seem desirable, it is possible to economize in the use of liming materials in the following ways: by exercising some choice in the crops to be grown; by reducing the losses of basic constituents in the drainage water through keeping the soil covered with vegetation a large part of the time; by selecting fertilizers that are neutral or alkaline in their effects on the soil; by plowing under well-decomposed organic matter to improve the buffer qualities of the soil; by arranging the crops in such order as to take advantage of marked differences in their need for lime; and by setting aside a restricted acreage on which to grow such high lime-requirement crops as may be required.

It is especially necessary to take these various methods of economizing on liming materials into consideration in the growing of crops of low acre value, or in any area that is so far removed from the source of lime as to make it very expensive. For crops of high acre value, considerations of economy in the use of limestone or its products may be largely set aside; although, even with high acre-value crops, the question of having the soil so buffered with organic matter as to prevent excessive fluctuations in its reaction, or in its content of soluble salts, merits considerable attention.

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CHAPTER XVIII

THE LIVESTOCK SYSTEM OF FARMING

In the livestock system of farming, it is possible to return to the soil a large proportion of the nitrogen and mineral nutrients that are removed from the field in crops. If a considerable percentage of the land is devoted to legumes, or if supplemental feeds are purchased and used in fairly large amounts, the total quantity of nitrogen that is applied to the soil in the form of manure may be in excess of that removed from it by crops and by the drainage water.

Ultimately, in any system of farming, a point is reached at which the return of nitrogen to the soil and the losses of this element from it attain a state of equilibrium, but in a well-managed system of livestock farming the soil content of nitrogen may be maintained at a somewhat higher level than is possible with other types of extensive farming. With the other nutrient elements, no such compensatory processes operate to make good the losses that occur as a result of the action of drainage water and from the sale of livestock and its products. This is particularly true with reference to the elements calcium and phosphorus. With calcium, the drainage losses are greater than those occasioned by crop removal. As to phosphorus, this element is found only in traces in the drainage water, but it is removed from the farm in considerable amounts in the bones of animals, including man, and in the milk and grain crops that are sold.

Nevertheless, the possibilities with reference to maintaining the productivity of the soil at a high level with the minimum expenditure for fertilizers are such, in livestock farming, as to merit its serious study from the point of view of realizing the maximum advantages of the system. Unfortunately, manure is subject to serious depreciation through loss of urine and as a result of leaching and hot fermentation. The theoretical and actual amounts of nitrogen and mineral elements that are returned to the soil may be quite different. It may be well to remember, also, that the use of purchased feeds involves the transfer of the essential elements from one farm to another, and makes no actual contribution to the solution of the problem of soil economy.

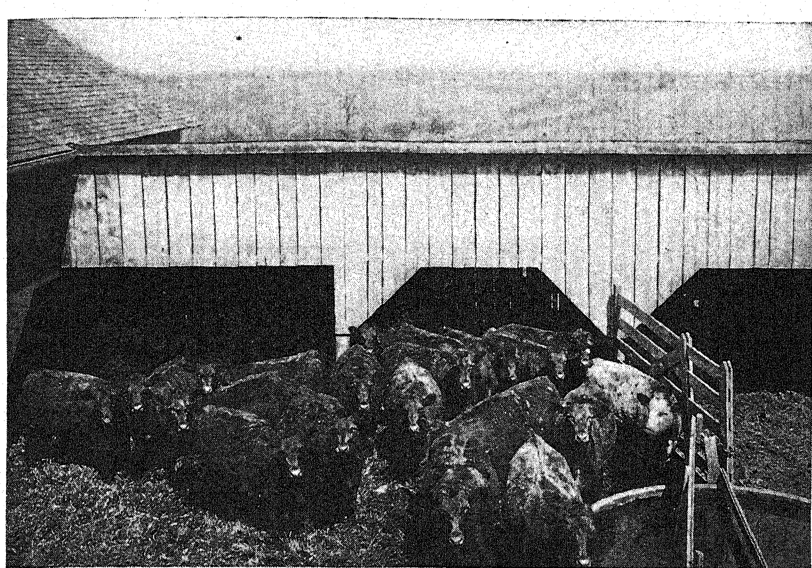


FIG. 32. In the best-developed systems of livestock farming, there is little loss of nutrient elements from the land.

NITROGEN AND MINERAL CONTENT OF ANIMAL BODIES

The amounts of nitrogen and mineral elements that are required in the construction of animal bodies have been the subject of very careful investigation. The original work on this subject was done by Lawes and his associates at Rothamsted and involved the complete analyses of the carcasses of a considerable number of animals. The data that are given in the accompanying table are for animals that were in good condition for market at the time of slaughtering.

The major portion of the ash of animal bodies is made up of phosphate of lime, most of which is contained in the bones. The content of phosphoric acid (P_2O_5) in an average 1000-pound steer is about 16

TABLE 95

POUNDS OF NITROGEN AND MINERAL OXIDES IN ANIMALS* (LAWES)

Material	Calf	Steer	Lamb	Sheep	Pig
N	24.6	23.3	19.7	19.8	17.7
CaO	16.5	17.9	12.8	11.8	6.4
P_2O_5	15.4	15.5	11.3	10.4	6.5
K_2O	2.1	1.8	1.7	1.5	1.4
MgO	0.8	0.6	0.5	0.5	0.3

* Calculated on the basis of 1000 pounds live weight of animal.

pounds, or the same quantity as is found in available form in a 100-pound bag of 16 per cent superphosphate.

NITROGEN AND MINERAL CONTENT OF MILK

The composition of milk varies considerably, depending upon the feed, the kind of animal, and the period of lactation. The data in Table 96 are taken from the analyses of eleven samples of milk from Holstein cows. The highest and lowest percentages of each constituent that were found are given for comparison. The calculations are based on 10,000 pounds of milk, or what might be considered a satisfactory annual production for one cow.

TABLE 96

POUNDS NITROGEN AND MINERAL OXIDES IN 10,000 POUNDS MILK (FORBES)

Material	Highest	Lowest	Average*
N	114.6	41.1	61.0
P_2O_5	26.8	16.2	23.0
CaO	24.2	9.0	15.2
K_2O	19.6	4.2	14.3
Cl	28.7	8.6	14.3
SO_3	18.8	5.8	10.5
Na_2O	19.3	3.3	8.5
MgO	3.3	2.0	2.4
Total ash	90.4	68.3	77.9

* From eleven analyses of milk from Holstein cows.

It is evident, from the above analyses, that the nitrogen and phosphorus contents of milk are relatively high. While the loss in nitrogen can be compensated for by bacterial fixation from the air in the growing of the necessary legumes for feed, that of phosphorus must be made good by the purchase of phosphate fertilizers. Assuming that each cow gave birth to a 90-pound calf and produced 10,000 pounds of milk during the year, approximately 1 ton of 20 per cent superphosphate would be required to compensate for the loss of phosphoric acid from the farm in the sale of these products from a herd of sixteen cows.

NITROGEN AND MINERAL CONTENT OF WOOL

The only other animal product that is of any significance in connection with the economy of the elements from the soil is wool. The chemical composition of this product varies considerably, depending largely upon the amount of suint that adheres to it. The quantity of this material is especially high on the wool of Merinos, of which it may constitute nearly 50 per cent. The following analysis is that of unwashed wool, from which is calculated the probable composition of the same wool after it had been freed of its suint.

TABLE 97

POUNDS OF NITROGEN AND MINERAL OXIDES IN 1000 POUNDS OF WOOL (LAWES)

Material	Unwashed	Washed
N	54.0	92.0
K_2O	56.2	0.0
CaO	1.8	3.1
P_2O_5	0.7	1.2
MgO	0.4	0.7

The losses here are primarily those of nitrogen and potassium. The latter element is removed from wool in the washing process and is thus recovered for use in the compounding of fertilizer mixtures. The annual loss of potassium from the sale of wool is equivalent to approximately 1 pound of muriate of potash for each sheep whose fleece is sold.

PERCENTAGE RECOVERY OF SOIL ELEMENTS IN MANURE

Since a certain amount of the nitrogen and mineral elements that are contained in crops are used by the animal and may later be sold from the farm in the form of the animal itself or its products, it is of interest to calculate the percentage recovery of these elements in the manure. It is apparent that, if the animal is a mature male and is used only for work purposes, every pound of these elements that is contained in the feed should be returned to the soil in the form of urine, feces, perspiratory products, and wastes of skin, hoofs, and hair. This means a 100 per cent recovery, assuming that the animal is kept on the farm all the time. In proportion as the animal is immature or is used for the production of milk, wool, or young, the percentage recovery in the excretory products is decreased.

Of interest in this connection is the balance sheet for a dairy cow. Such balance sheets for a number of different cows, all of the Holstein breed, were calculated by Forbes, and one is presented in Table 98.

The experiment from which the above data were calculated was carried out for nine days during the fifth month of the period of lactation. The cow was not bred. Her average daily production was 37.9 pounds of milk. The totals for the milk, urine, and feces were slightly larger for most of the elements than were those in the feed. The only explanation for this lies in the assumption that something was con-

TABLE 98

BALANCE SHEET FOR PRODUCTION OF 10,000 POUNDS OF MILK (FORBES)

Material	Food, Pounds	Milk, Pounds	Urine, Pounds	Feces, Pounds	Recovery* Per Cent
N	171.0	44.3	65.6	61.1	74
K_2O	98.0	14.9	76.7	6.4	85
CaO	82.7	14.6	1.3	66.8	82
P_2O_5	51.1	19.3	0.5	31.3	62
SO_3	42.3	6.8	16.0	19.5	84
MgO	34.7	2.2	3.6	28.9	94
Cl	20.3	10.9	4.6	4.8	46
Na_2O	17.5	4.7	9.2	3.6	73

* Percentage of the nitrogen and minerals of the feed that were contained in the combined liquid and solid excrements.

tributed by the feeds that were given the cow before the experiment was begun. These differences are accounted for in the table by adding them to the food consumed. These and other tests indicate that, for a milk cow, the percentage recovery of the phosphorus is less than that of any other essential element. Additional losses of some of these elements would have occurred in the event that the cow had been pregnant. On the other hand, if the cow had been dry, a large percentage of the constituents would have been recovered in the urine and feces.

RELATIVE AMOUNTS OF CONSTITUENTS IN URINE AND FECES

Some idea of the distribution of the soil elements, as between the urine and feces, may be gained from the data in Table 99 taken from the investigations of Forbes and his co-workers. The comparison is be-

TABLE 99

PERCENTAGE DISTRIBUTION OF MATERIALS BETWEEN URINE AND FECES (FORBES)

Material	Dry Cow		Milking Cow	
	Urine	Feces	Urine	Feces
K_2O	95	5	92	8
Cl	75	25	48	52
Na_2O	74	26	73	27
N	63	37	51	49
SO_3	51	49	44	56
MgO	11	89	12	88
P_2O_5	1	99	2	98
CaO	0	100	1	99

tween two cows, one of which was dry and was in the ninth month of the period of gestation, while the other had not been bred but was in the fifth month of the lactation period.

Over 90 per cent of the potassium and somewhat more than half of the nitrogen were contained in the urine, while most of the calcium and phosphorus were voided in the feces. Studies with pigs indicate a similar distribution except that slightly more phosphorus and sulfur and less potassium are contained in the urine.

WATER-SOLUBLE CONSTITUENTS IN MANURE

Manure is made up of urine and feces mixed with bedding and residues from the feed. One might assume that, if it were subjected to the leaching action of rains, the loss would be simply that of the urine. Experiments to determine this point indicate that considerably more than the urine may be leached from the manure heap. The following data show the content and percentage solubility in water of the nitrogen, phosphorus, and potassium of manure. This manure was sampled as it came from the feeding stalls where it had been protected against loss of urine and presumably against hot fermentation. Of particular interest is the solubility of phosphorus, which is almost entirely excreted in the feces.

TABLE 100

COMPOSITION OF MANURE FRESH FFOM FEEDING STALLS (AMES)

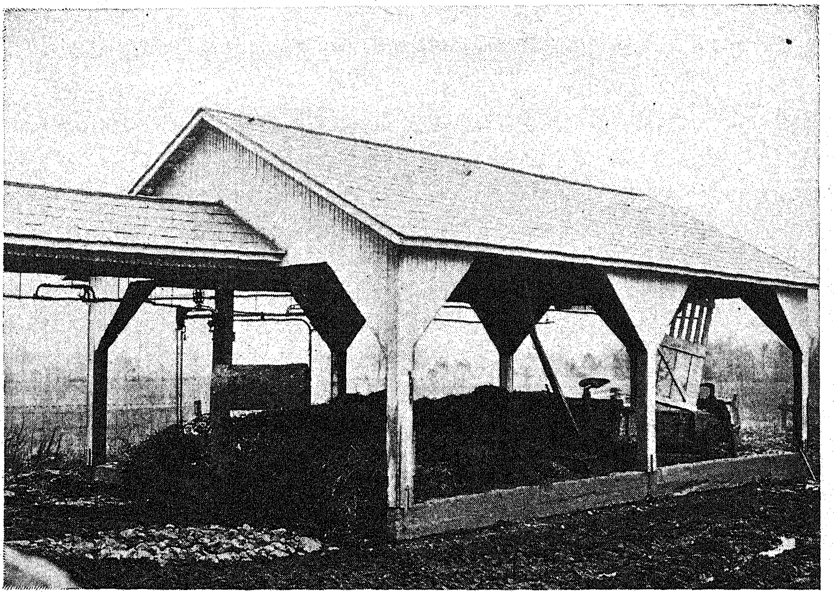
Kind of Animal	Per Cent of Water	N		P_2O_5		K_2O	
		Per Ton, Pounds	Water-soluble, Per Cent	Per Ton, Pounds	Water-soluble, Per Cent	Per Ton, Pounds	Water soluble, Per Cent
Poultry*	68	28.8	..	19.8	..	7.8	..
Sheep	64	28.7	42	10.1	58	25.0	97
Steer	78	14.3	55	9.4	36	10.9	92
Horse	59	13.9	52	4.8	53	15.2	75
Cow	79	11.4	50	4.4	50	12.5	97
Hog†	87	10.0	..	7.0	..	8.0	..

* Brooks, Circ. 54, Mass. Agr. Exp. Sta.

† Van Slyke, Soils and Fertilizers.

POSSIBLE LOSSES FROM UNPROTECTED MANURE

Often, the losses of mineral elements and nitrogen from the livestock farm in the sale of animals, milk, and wool are less than those that occur in the careless handling of manure. These losses may result from failure to haul the manure to the field, from lack of facilities for conserving the urine, from leaching, and from hot fermentation. If the urine is not absorbed by straw, it must be caught in a covered cistern in order to prevent the loss of nitrogen by volatilization as ammonium carbonate. The possibilities of loss from leaching are indicated in Table 100. As manure undergoes decomposition, additional amounts of each of the soil elements become soluble and, if the manure is exposed to the weather, it may be leached out. It is desirable that



Portland Cement Association.

FIG. 33. In order that manure may sustain as little loss of the essential elements as possible, it is important that it be covered with a roof and be stored on a tight floor.

manure go through a "ripening" process before it is applied to the field; but, if this is permitted, the manure should be stored under cover and on a watertight floor, otherwise more may be lost than is gained in the process.

The heating of manure is caused by rapid bacterial oxidation, which results in high temperatures and consequent volatilization of the nitrogen. Horse, sheep, and poultry manures are especially subject to "fire-fanging" by reason of their low content of water. The prevention of such losses can be accomplished by keeping the manure wet and compact. Under such conditions, the decomposition processes are largely anaerobic and high temperatures are not developed. The previously insoluble mineral and nitrogen compounds gradually become soluble while the carbonaceous materials are broken down into carbon dioxide and water. When this happens to the carbonaceous materials, there is little loss of ammonia because of the concentration of carbon dioxide, in an atmosphere of which ammonium carbonate is stable. Some loss of nitrogen by volatilization is sure to occur, but the evidence indicates that this need not be serious if precautions are taken to mix the manure from the different classes of animals and to have it well tramped, or to keep it practically saturated with water. When such manure is incorporated with the soil, the products of protein hydrolysis rapidly yield up their nitrogen as ammonia, and conditions are favorable for its oxidation by the nitrite and nitrate bacteria.

Considerable attention has been given to the use of preservatives on manure. Of these, the most promising material from the point of view of preventing loss of ammonia is the monocalcium phosphate. Superphosphate is the commonly used carrier of this compound. It usually contains a considerable percentage of gypsum and serves as a supplemental source of calcium and phosphorus to the manure, both of which increase its value as a soil-improving agent.

MANURE AS A CROP-PRODUCING AGENT

If it is remembered that nitrogen can be secured from the air by growing legumes; that, if these legumes are fed to livestock, 75 per cent of their nitrogen is voided in the urine and feces in the case of dairy cows, and considerably larger amounts with other classes of animals; that the careful saving of the manure will permit the return of most of this nitrogen to the field; that soils, as a rule, are relatively high in their content of potassium, additional quantities of which can be made available by good management; and that 85 per cent or more of the amount of this element in the feed is excreted by the animals that eat it; then it would seem that, by the return to the fields of the manure produced from feeding a large portion of the crops that are grown on the farm, it should be possible to maintain the yields of crops at a fairly high level. Where soil is kept supplied with limestone and the manure is supplemented with enough phosphate to compensate for the loss of this material in the bones and milk, this has been shown to hold true.

An interesting test of manure as a crop-producing agent is afforded in Table 101. In this test, 8 tons of manure were applied to the clover sod in a three-year rotation of corn, wheat, and clover. At the beginning of the test, in 1897, the soil was in a relatively low state of productivity and, for that reason, the average yields were not as high as they might otherwise have been. Limestone had been used as required for satisfactory stands of clover.

TABLE 101

AVERAGE* ACRE YIELDS WITH 8 TONS OF MANURE ON CORN (THORNE)

	Corn, Bu.	Wheat, Bu.	Clover, Cwt.
Phosphated manure†	67.7	28.6	49.0
Stall manure	61.9	23.8	41.5
Open-yard manure	55.9	22.8	36.6
No manure	36.8	14.2	29.4

* Twenty-six year averages.

† Sixteen per cent superphosphate, at a rate of 40 pounds per ton, was scattered over the manure before it was hauled to the field.

Keeping the manure under cover not only permits of having more tons of manure, but a ton of stall manure is considerably more valuable than is one from the open yard. The addition of superphosphate further increases the effectiveness of the manure. Unfortunately, in this, as in most other tests of which records are available, the manure used is not that produced from feeding the crops that are grown on the land to which it is applied, but such manure as is available on the farm from year to year.

A somewhat better idea of the possibilities of crop production in the livestock system of farming is to be found in another test, data for which are recorded in Table 102, in which the manure resulting from feeding the crops to steers is returned to the fields on which the crops that are fed were produced. The manure is supplied to the corn crop in a four-year rotation of corn, soybeans, wheat, and clover. All the crops are fed or used as bedding with the exception of the wheat grain. In addition to the manure, 2 tons of limestone and 400 pounds of 16 per cent superphosphate are applied for the corn, and 300 pounds of additional superphosphate for the wheat. This is compared with a

TABLE 102

AVERAGE* ACRE YIELDS IN LIVESTOCK AND GRAIN FARMING (WILLIAMS)

Crops	Livestock System†	Grain System	Difference
Corn, bu.	73.5	66.7	6.8
Soybeans, bu.	22.6	19.6	3.0
Wheat, bu.	33.9	30.2	3.7
Clover, cwt.	44.0	....	...

* Sixteen-year averages.

† The average annual manure production has been 3.9 tons per acre, or 15.5 tons per acre for applying to the clover sod to be plowed under for corn.

system of grain farming in which the corn, soybeans, and wheat grain are sold, and the clover, straw, and other crop residues are plowed under. The same amounts of superphosphate and limestone are used in the grain system of farming as in the livestock system.

AMOUNT OF MANURE PRODUCED BY ANIMALS

In the above test, the grain, hay, and stover are fed to cattle which are allowed to run loose in a covered yard. The straw is used for bedding. The annual acre production of manure has averaged nearly 4 tons. The amount of manure produced has been 1½ times the air-dry weight of the feed and bedding. While the total excrement, plus the bedding, amounted to considerably more than this, the losses in weight by oxidation and evaporation were evidently quite rapid. The daily excrement of animals varies from perhaps 25 pounds per thousand pounds live weight, in the case of poultry, to as much as 75 pounds for the same weight of hogs, with intermediate amounts in the case of sheep, steers, horses, and cows, whose daily production for equal live weight is in the order in which they are named. In calculating the quantity of manure that will be hauled to the field on the ordinary farm, the factor 1½ times the dry weight of the feed and bedding is probably as high as can be safely applied, even assuming that the manure is kept under cover until it is hauled to the field.

IMPROVING THE QUALITY OF MANURE

The quality of manure may be improved by reinforcing it with some carrier of phosphorus, by the use of concentrated feeds, and by carrying it through a ripening process under such conditions as will not permit of serious loss of its nitrogen and mineral nutrients through volatilization and leaching. The effect of the supplemental applications of superphosphate has been previously noted. The use of concentrated feeds is of especial interest, since by this means it is possible to exercise a choice between purchasing plant nutrients for fertilizer purposes only and purchasing them in the form of protein feeds out of which both a feeding and a fertilizing value may be realized. While these protein feeds are purchased primarily for their protein, fat, and carbohydrate content, they also carry considerable amounts of mineral nutrients, as is indicated in Table 103.

From 75 to nearly 100 per cent of the nitrogen and mineral nutrients of the feed can be recovered in the manure, depending upon the age of the animal and the use to which it is put. A ton of cottonseed meal contains as much phosphorus as is found in nearly 200 pounds of 16 per cent superphosphate, as much nitrogen as is contained in 350 pounds of nitrate of soda, and additional amounts of other mineral nutrients. By the time the cottonseed meal has passed through an animal body, its plant nutrients are in a state of availability that is equal to that of the same constituents in the higher grades of commercial fertilizer. Similarly, animal tankage has a very high supplemental fertilizer value after its feeding value has been realized.

It is evident that the manure from animals that are fed corn stover, timothy hay, and oats straw is much less valuable than that which is produced from feeding legume hays, grains, and supplemental concentrates. It is also apparent that in proportion as the concentration of

TABLE 103

COMPOSITION* OF STANDARD CONCENTRATED FEEDS (FORBES)

Feed	N	P_2O_5	K_2O	CaO	MgO	SO_3	Na_2O
Animal tankage	93.7	37.4	6.6	41.3	2.4	15.2	22.5
Soybeans	63.0	13.6	23.0	2.9	3.7	10.2	4.6
Cottonseed meal	57.4	31.1	19.9	3.7	9.0	12.3	3.5
Linseed meal	56.8	16.2	13.2	5.1	8.1	10.2	3.4
Gluten feed	44.0	12.5	3.0	3.5	3.6	3.5	5.7
Wheat bran	25.2	25.5	15.8	1.8	8.8	1.8	2.7
Alfalfa hay	23.0	5.1	9.2	14.6	6.1	6.9	6.1

* Pounds in 1000 pounds of feed.

nitrogen and mineral nutrients in the manure is increased, the opportunity for loss by careless handling of the manure is also much greater. The use of concentrated feeds, therefore, justifies a larger investment in improved storage facilities by which losses of the manurial constituents may be prevented.

THE COMPOSTING OF MANURES

The difficulty with grain farming, as practiced in the experiment recorded in Table 102, is that large amounts of coarse vegetable matter, low in nitrogen, are plowed under. It is probable that the crop yields would have been larger if fertilizer nitrogen had been applied over the cornstalks and wheat straw before they were plowed under, in order to supply the needs of the cellulose-decomposing bacteria for this element. This is one reason why well-rotted manures are preferred to strawy manures, particularly if they are to be used in as large amounts as they often are in vegetable and flower gardening. It must be admitted that the losses that may occur in the rotting processes may be considerable unless precautions are taken to keep the manure under cover and to keep it moist. Nevertheless, gardeners go to considerable trouble and expense to compost manure, both for the sake of solubilizing its nitrogen and mineral nutrients and of getting rid of the excess of cellulose materials.

The *composting* of manure is effected by building a heap of alternate layers of manure, soil, and sod, with which may be incorporated any available refuse material that is not diseased. This is kept moist until the process of decay is well under way, when the heap is turned. An intimate mixture of soil and well-decomposed organic matter is thus effected. This is ideal for use in the soil-compost mixture that is to be used in plant beds and flower pots. In the soil-compost mixture, use is also made of leaf mold, which is produced by piling the leaves in some out-of-the-way corner where they are allowed to undergo the natural process of humification for a period of two to three years. When these compost materials and leaf mold are placed in the flower pots, the conditions as to aeration and moisture supply may be almost ideal. The organic materials afford a satisfactory buffer against overwatering or overfeeding.

In China and Japan, clover and canal mud are used for compost purposes, these materials being arranged in alternate layers and well compacted. When the fermentation process has taken place, the compost is spread over the land and is subsequently worked into the soil. When composts are added to the soil, rapid nitrification takes place, and the resulting nitrous acid may react with the soil minerals to liberate additional amounts of the inorganic nutrients.

PRODUCTION AND VALUE OF ACTIVATED SLUDGE

In Asiatic countries, extensive use is made of human excrement for soil purposes. Elaborate precautions are taken to conserve such materials and to apply them to the field. Modern sanitary requirements do not permit such practices in this country. Considerations of economy, as well as those of sanitation, justify the assumption that methods of sewage disposal which destroy the pathogenic species of bacteria and conserve the sludge materials will ultimately come into general use. By the *activated-sludge* method of sewage disposal, these desirable results are accomplished In this process the sewage is collected in tanks, through which air is blown. The sludge which settles out after this operation is found to possess the remarkable quality of effecting a rapid oxidation of the organic matter in fresh sewage, leaving a residue that is practically free of intestinal bacteria and that is of such a nature as to possess considerable value for fertilizing purposes.

The resulting product, when dried, contains 3 to 6 per cent of nitrogen and 3 to 4 per cent of phosphoric acid in forms that readily become available for plant use when applied to the soil. The per capita production of this material is estimated at 135 pounds a year. The amount that may ultimately become available is quite large.

"SYNTHETIC" MANURE

In some types of farming, little or no livestock is available for converting refuse plant materials into manure. Even on farms on which a considerable amount of livestock is kept, there is often more straw and similar materials than can be used for bedding. In continental Europe, it is the practice to put such materials into pits or to pile them into heaps whose tops are so built as not to shed the rain, and to water these heaps from time to time with urine. In the event that insufficient urine is available for this purpose, supplemental use is sometimes made of a dilute solution of sulfate of ammonia. Experience indicates that the concentration of this solution should not exceed 5 per cent.

Experimental work at the Rothamsted Station in England has shown that the requirements for rapid decomposition of straw and similar highly carbonaceous materials are an adequate content of moisture in the heap and the use of suitable amounts of some carrier of readily available nitrogen. The process of decomposition is further hastened by the additional use of available phosphates and small amounts of lime.

The straw, or similar material, is built up into a heap by layers 1 foot in thickness, each of which is wet with water and sprinkled with the mixture of fertilizer salts. The heap is built to a height of at least 6 feet and is then kept moist while decomposition is taking place. A rise in temperature is soon noted, and at the end of a period of about three months the whole heap has been transformed into manure of a quality quite similar to the ordinary barnyard variety, if the conditions as to moisture supply have been kept at or near the optimum. One ton of straw, treated with 150 pounds of a half-and-half mixture of ammonium sulfate and lime, will make approximately 3 tons of manure. The analysis of one sample of such manure showed a content of 2.19 per cent of nitrogen, 1.20 per cent of phosphoric acid (P_2O_5), and 0.58 per cent of potash (K_2O). Great interest has been aroused in this method of making manure. Large amounts of straw are available for this purpose in the Wheat Belt. The leaves of trees in forests and around parks and homes can be made into excellent compost by this means.

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CHAPTER XIX

SOIL SANITATION

As soils become older agriculturally, they tend to decrease in productivity. In the nomadic period of civilization, the solution of the problem of unproductive soils was found in a change of habitation. Later it became desirable to continue to cultivate the same land for an indefinite period, and it was then necessary to study the possibilities of other means of overcoming the tendency toward reduction in yields. Jethro Tull, in 1733, was of the opinion that the solution lay in the more intensive cultivation of the soil. To that end, he grew his wheat in rows that were far enough apart to permit intertilling. Marked improvements in tillage implements were stimulated by Tull's teachings.

Liebig, in 1840, suggested a chemical solution based on the theory that plants remove elements from the soil more rapidly than the supply is renewed, and that the lack of one or more of these elements becomes the limiting factor in crop production. This was the beginning of the fertilizer industry. Later, a school of bacteriologists, of which the pioneers were Schloesing and Muntz, Hellriegel and Wilfarth, Winogradsky, and Beyerinck, outlined a biological explanation of the differences in the productivity of soils. The practices of inoculation and sterilization of soils had their origin in this period. Continued investigation has shown that, in order to maintain and increase the productive capacities of soils, consideration must be given to all of the various physical, chemical, and biological factors that operate in them, and that the effects of these factors may be either positive or negative, depending upon the conditions that obtain.

SOME NEGATIVE PHYSICAL FACTORS

Of the various controllable physical factors that may operate negatively in their effects on the growth of plants, water is probably the most important. The temperature of the soil, the nature of the solution that it offers to the roots of plants, the character of its microbiological population, and their combined effects on plants are determined in large part by the conditions as to the supply of water in the soil. In proportion as the content of water increases above the optimum, which is normally about two-thirds of the amount required for saturation, most crop plants are injured. For this reason, considerable pains are taken to drain away the excess of water from soils and to keep the water table under control.

When virgin soil is put under cultivation, certain changes tend to take place which make it less pervious to water and more in need of artificial drainage. The surface accumulation of organic matter soon undergoes decomposition. The channels left behind by the decay of plant roots, particularly those of trees, become filled with soil. The number of earthworms and other burrowing forms of life tends to decrease, with a reduction in the amount of organic matter and an alteration of the moisture relationships in the soil. The net effect of all these changes is a slowing down of the rate of percolation of water through the soils of the silt-loam and clay-loam classes until it may become necessary to install a complete system of artificial drainage on land that previously could be farmed by the use of only occasional lines of tile. Otherwise, conditions in these areas of wet land, which become larger each year, are such that anaerobic decomposition gains the ascendency, toxic reduction products tend to accumulate, fixation of nitrogen is confined to the activities of the *Clostridium pastorianum* forms of bacteria, nitrification is very much reduced, and the growing of crop plants becomes more and more difficult.

SOME NEGATIVE CHEMICAL FACTORS

It will be recalled that the toxicity of acid soils is not altogether a matter of the concentration of hydrogen ions but also of the increased solubility of aluminum and manganese. Certain other elements, such as arsenic, zinc, lead, and copper, may be soil-contaminating agents in the vicinity of smelters or may accumulate in the soil as a result of the use of spraying materials. In the consideration of the nature of the soil solution, it was pointed out that its reaction, the ratios in which the various ions are present, and the total concentration of salts, unless kept within fairly narrow limits, may operate as negative factors in relation to the productivity of soils.

Fortunately, the concentration in the soil solution of such ions as aluminum, zinc, and copper can ordinarily be reduced below their point of toxicity by controlling the reaction of the soil between somewhat narrow limits. This is indicated by the data in Table 104 which show the solubility of salts of aluminum and its content in the soil solution as determined by the reaction.

It will be noted that the concentration of soluble aluminum is least when the reaction of the solution is kept between pH 5 and 7. This

TABLE 104

Parts per Million of Al_2O_3 Soluble in Water (Magistad)

pH	$AlPO_4$*	$Al_2(SO_4)_3$	Soil
4.0	4.4	153.4	231.2†
4.5	0.3	7.8	3.0†
5.0	0.0	1.6	1.6
5.5	0.0	0.8	0.3
6.0	0.0	0.4	0.4
6.5	0.0	0.3	0.6
7.0	0.0	0.4	2.1
7.5	1.8	1.9	9.3
8.0	2.0	5.6	16.3

* Solubility of aluminum phosphate (as Al_2O_3) in approximately a 1 per cent solution of sodium acetate.

† These soils were made more acid by the addition of sulfuric acid. The soil solution was secured, in each case, by displacement with alochol.

indicates the necessity of the use of limestone on acid soils for the satisfactory growth of all those crops that are sensitive to soluble aluminum. The presence of the phosphate ion tends to reduce the solubility of aluminum. Superphosphate serves an important function in this connection on acid soils although its use for this purpose is not as economic as that of hydrated lime or ground limestone.

It happens that certain plants, of which notable examples are the rhododendrons and blueberries, grow satisfactorily only under conditions in which the soil is acid and thrive in the presence of relatively high concentrations of aluminum. When it is desired to grow such plants on soils that are neutral or alkaline in reaction, aluminum sulfate is mixed with the soil in which they are planted and is scattered over the surface of the soil from time to time afterward, in order to meet their requirements. Equally good results may be secured by the use of sulfuric acid or free sulfur, or the incorporation of sawdust, oak leaves, and similar acid-forming materials with the soil.

Sometimes, the addition of lime in excessive amounts results in a deficiency of manganese, iron, zinc, and boron, and their lack becomes a limiting factor in crop production. It will also be noted that, when the reaction of the soil passes the neutral point in the direction of alkalinity, the concentration of aluminum in the soil solution is increased. For these and other reasons it seems advisable to maintain the reaction of the soil at a point that is at least not in excess of pH 7, and for many crops it must be reduced to as low as pH 5 for satisfactory results.

POSSIBLE TOXICITY OF FERTILIZER SALTS

Toxic effects on crops have been noted as the result of the use of a number of fertilizer salts, of which the most outstanding examples are sulfate of ammonia, calcium cyanamide, and certain potash fertilizers having their origin in this country. In the first example, the difficulty lies in the tendency to increase the acidity of the soil. This may be overcome by the use of somewhat larger amounts of lime. The injury that has been noted following the use of calcium cyanamide is the result of the temporary presence of intermediate toxic products of hydrolysis which are especially injurious in sandy soil. Application to the soil a few weeks in advance of planting the crop is necessary if large amounts of this product are to be used. A contaminating agent that was found in certain American potash salts has been shown to be borax. The effects of this compound on the yield of certain crop plants is shown in the Table 105.

Before the toxic effects of borax were known, considerable acreages of potatoes and other crops were almost completely destroyed as a result of the use of potash fertilizers containing this material. When

TABLE 105

EFFECT OF BORAX ON ACRE YIELD OF CROPS* (SKINNER)

Borax, Lb.	Lima Beans, Cwt.	String Beans, Cwt.	Potatoes, Bu.	Corn, Bu.
0†	53	59	167	127
3	63	61	180	104
4	59	56	250	94
5	75	47	153	98
10	46	34	180	94
20	56	25	144	92
30	32	20	117	78
50	26	6	108	77
100	7	3	68	12

* Silty clay-loam soil. The fertilizer was applied in the row at the time of planting.

† Averages of several check plots distributed among those that received the various amounts of borax.

it was discovered that borax was the toxic agent, such processes of refinement were put into operation as are required to free the potash salts of this material. It will be noted that small amounts of borax tend to have a stimulating effect on plants. This also holds true for salts of zinc, arsenic, and a number of other elements with which tests have been made.

From the above considerations, it is evident that care must be exercised in the use of chemical substances of a toxic nature on soils. Salts of copper, lead, zinc, and mercury are used in a variety of ways in the control of insects and diseases. Under conditions in which these elements accumulate, toxicity results unless the reaction of the soil is kept approximately neutral. With such materials as borax, cyanamide, and salts of arsenic, simply regulating the soil reaction is not effective. Ultimately, any excess of soluble toxic compounds may be leached from the soil, but meanwhile the land will support little or no vegetation. Some difficulty from toxicity has been experienced from the use of arsenical dusts on cotton growing on acid soils. Washington and Oregon apple growers have also been troubled from soil poisoning after using arsenical sprays. Hydrated iron oxide, or bog iron ore, is used as a corrective. There is great need for better organic insecticides that leave no toxic residues.

NEGATIVE BIOLOGICAL FACTORS

The negative factors that are of primary concern in the problem of soil sanitation are those that are biological in nature and include such agents as disease-producing microorganisms, insects, and weeds. The control of these factors may affect the policy of the farmer in connection with his system of soil management. It is partly because of this that crop rotation has received so much attention. This practice not only has the effect of regulating the supply of available nitrogen and mineral nutrients in the soil but also provides a means of holding in check certain negative biological agents. With more intensive cultivation, it has been found necessary to take especial precautions to control plant parasites which live in the soil, both by prevention of unnecessary contamination of the soil and by checking the abnormal development of the parasites after they have been found to be present in the soil. In doing this, various methods have been employed, such as sterilization by heat and antiseptics, control of the soil reaction, and the development of disease-resistant strains of plants.

SANITARY REASONS FOR CROP ROTATION

Of considerable interest in this connection is the point of view expressed by Bolley who has called attention to the problem of soil sanitation in relation to the growing of wheat under the continuous-cropping system that has been practiced in the Dakotas. In his opinion, the explanation of the reduction in yields, which is commonly experienced under such conditions, is to be found in the accumulation in the soil of parasitic organisms that attack not only the above-ground portions of the plants but their roots as well. Bolley states that the good effects of proper tillage, crop rotation, and the use of fertilizers and lime are often indirect in that they serve as means of controlling parasitic organisms, by making conditions either unfavorable for the parasites or especially favorable for the host, thereby enabling the latter to resist the invasion of its enemies.

The virulence of parasitic bacteria is often found to be related to the frequency with which they have opportunity to live within the tissues of their host. Crop rotation is a means of reducing this frequency. The outstanding example of the long rotations that are designed to meet this condition is that which is used in Russia and other European countries for the control of the wilt disease of flax. The rotations that are normally recommended contain flax only once in 7 to 10 years, and sometimes the flax crop does not return to the same land oftener than once in 20 years. The history of this crop in the United States shows that flax production has been constantly shifting westward in keeping with its need to be grown on new soils that have never produced this crop and are, therefore, free of disease.

Considerable difficulty has been experienced with red clover in the Corn Belt, where this crop normally appears every third or fourth year in the rotation. It is commonly believed that much of this difficulty lies in the attacks of parasitic organisms, of which an anthracnose (*Colletotrichum trifolii*) is one of the most serious. It is interesting to note the yields of clover that have been produced where the crop is grown continuously, as it has been on some rich garden soil at Rothamsted. The yield records since 1854, calculated on the acre basis, are given below.

TABLE 106

Average Acre Yields of Red Clover Grown Continuously (Rothamsted)

Number of Years	Hay, Cwt.	Dry Matter, Cwt.	Nitrogen, Lb.
First 25 years	76.6	63.8	179
Second 25 years	39.2	32.7	101
Next 20 years	26.4	22.0	65
For 1923	14.7	12.3	37
For 1924	7.9	6.6	20

A variety of other explanations can be given for the reduced yields or failures of clover. Among these may be mentioned the reaction of the soil, its deficiency in mineral nutrients, and the use of seed from southern European countries. If the difficulty lies in the increase in the number and effectiveness of parasitic organisms, then it is necessary either to change the cropping system or to sow seed of one of the disease-resistant strains of clover now available. Fortunately, alsike clover and sweet clover are not attacked by anthracnose. One or the other of these clovers can be substituted for red clover until the soil is freed of this disease. Similar rotation suggestions have been made in connection with the control of other parasitic organisms which harbor in the soil. There is need to investigate rotations from the point of view of their length and the crop sequence as related to soil sanitation.

DISSEMINATION OF PLANT DISEASE IN MANURE

Another interesting statement made by Bolley, of North Dakota, is that the manure spreader is a very effective agent for disseminating plant-disease organisms. This would indicate the necessity for composting the manure in order that the heat of fermentation may be utilized in the destruction of these organisms. Other plant pathologists point out that certain types of refuse from diseased plants should not be permitted to get into the manure heap. The advisability of feeding the refuse of cabbage and similar crops to livestock is questioned. Notable examples of the almost complete loss of this and other of the more specialized crops, from parasitic bacteria that have accumulated in the soil under intensive systems of cropping, are known. This is particularly likely to occur where little care is exercised to prevent the spread of organisms by the application of contaminated manure or from the use of plants from beds that were filled with them.

It is evident that commercial fertilizers have some advantages over manure, in this connection, since they are not likely to carry disease organisms. Fertilizers are also valuable as carriers of readily available nutrients in well-balanced ratios which may aid the plant in developing disease resistance. Calcium cyanamide has disinfecting properties; but, if it is applied in sufficient amounts to secure such effects, the application must be made some weeks in advance of planting the crop in order that the toxic compounds may disappear before that time. Common salt is sometimes applied in large amounts to beds of asparagus to kill the weeds, advantage being taken of the tolerance of the asparagus for high concentrations of salts. Similar advantage may be taken of differences in the tolerance for acidity of the host and its parasite in the use of sulfate of ammonia for potatoes as an aid in the control of scab.

An interesting example of this is shown in the data in Table 107, secured in connection with experiments on various carriers of nitrogen for potatoes. The average acre yields and the degree of scabbiness of the potatoes are given for a two-year period.

TABLE 107

SCABBINESS OF POTATOES AS RELATED TO FERTILIZERS EMPLOYED (MARTIN)

Special Treatment	Acre Yield, Bu.	Clean, Per Cent	Salable,* Per Cent	Unsalable, Per Cent
No nitrogen	122	20	48	32
Nitrate of soda	212	12	48	40
$\frac{2}{3}$ nitrate — $\frac{1}{3}$ sulfate	239	35	46	19
$\frac{1}{3}$ nitrate — $\frac{2}{3}$ sulfate	249	38	47	15
Sulfate of ammonia	216	42	44	14

* These potatoes were scabby but salable.

DISEASE-RESISTANT STRAINS OF PLANTS

Considerable attention is being given to the selection and propagation of disease-resistant strains of plants. Notable examples are rust-resistant wheats, chinchbug-resistant sorghums, and fire-blight-resistant pears. In Wisconsin, Jones and his co-workers achieved marked success with yellows-resistant cabbage. The Kentucky Experiment Station has developed a strain of red clover with an increased resistance to anthracnose. The iron cowpea, Dillon cotton, Scott carnation, and Kieffer pears are well-known examples of strains or varieties that are not troubled with the diseases commonly affecting these plants.

While disease resistance may be inherited, it is a quality that is somewhat dependent upon the climatic and soil conditions. Thus, in the selection of yellows-resistant strains of cabbage, it has been shown that seedlings of the resistant strains, when grown in an infested soil at temperatures of 17° C. (62° F.) and above, succumb almost as readily to the disease as do those of the susceptible strains. After a few weeks' growth, however, a high degree of resistance is acquired. This indicates the desirability of early planting or of using such methods of soil management as will maintain a relatively high content of moisture in the soil as a means of keeping the temperature down during the early stages of growth of this crop.

A knowledge of the conditions of the soil as to the temperature, moisture content, reaction, and other properties which will best aid in the control of specific parasites, is desirable. When these are known, it may be possible to change the system of management of the soil, to alter the time of planting, or to select a class of soil that is better suited to the maintenance of favorable conditions for the crop.

Wisconsin Exp. Sta.

FIG. 34. Effect of cabbage yellows.

STERILIZATION OF SOILS

The control of diseases can be effected in a small way in the greenhouse and in plant beds by sterilization of the soil. Formalin and steam are the two materials that are commonly employed for this purpose. Carbon bisulfide is used to good effect in the control of the Japanese beetle which harbors in the soil around the roots of nursery stock. Paradichlorbenzene and ethylene dichloride are effective weapons against peach-tree borers. Organic mercury compounds will eradicate the *brown patch* disease of putting greens. Chlorpicrin, methyl bromide, and diethyl ether are being used for sterilizing plant beds.

There is need for the development of some method for the sterilization of soils in an extensive, field way. Such materials as bleaching powder have been suggested. When this comes in contact with moist soil, it liberates chlorine and leaves an alkaline residue. Kainit and common salt have also been used for this purpose, but the nature of their action is not definitely known. There is opportunity for regulating the reaction of the soil at a point that is unfavorable for the parasite but not for the host. The use of quicklime for the eradication of the clubroot of cabbage and the use of sulfur as a means of controlling the potato scab are good examples of this method. It is possible that market gardeners could make use of sulfur and limestone to cause such marked fluctuations in the reaction of the soil, during periods when crops were not being grown or in connection with the growth of crops that are tolerant of acid and alkaline conditions, respectively, that the soil could be kept relatively free of disease-producing organisms and insect pests. It would probably be necessary to re-inoculate with desirable bacteria by the use of soil from areas on which the market-garden crops were not being grown.

PHAGOCYTIC THEORY OF SOIL INFERTILITY

In investigating the relation of temperature to oxygen absorption by soils, Russell and Hutchinson, of Rothamsted, found that the rate of absorption was very much increased by partial sterilization of the soil. Further study of this problem led them to believe that ordinary soils contain some factor which is inimical to the development of bacteria. They later came to the conclusion that this factor is the presence of soil protozoa and that the abnormal bacterial development following partial sterilization is due to the destruction of these phagocytes.

The phagocytic theory of soil infertility gave rise to a considerable amount of discussion and investigation on the use and effects of heat and volatile antiseptics as partial sterilizing agents in soils. As a result, it has been shown that the effect of such materials is to reduce, temporarily, the number of bacteria in soils, but that this reduction is later followed by an abnormal increase in their number and by a marked stimulation of the growth of plants that may be set in the soil. While it is known that the chemical composition of the soil solution is altered and that the biological activities in the soil are profoundly influenced by partial sterilization, much remains to be done to determine the initial effects of the process which precede the phenomena that have come under observation.

An example of the effect of partial sterilization on the increase in the number of bacteria in soils is given in Table 108. In this test, carbon bisulfide was used as the sterilizing agent.

Such a marked effect on the number of bacteria must be accompanied by considerable changes in the availability of the nitrogen and mineral elements in soils. It has been found that, in proportion as the number of bacteria become greater, there is an accumulation of ammonia which is followed later by a corresponding increase in the nitrate content of the soil.

TABLE 108

EFFECT OF CARBON BISULFIDE ON THE NUMBER* OF BACTERIA (FRED)

Time in Days	Control Soil	Treated with CS_2
1	11	1
3	22	23
5	20	25
9	14	36
13	16	90
21	19	60
25	18	68
29	15	90
60	12	58

* Millions of aerobes per gram of soil.

INSECTS AS NEGATIVE FACTORS

Insects constitute a second group of biological agents, most of which function negatively. In order to control them, it may be necessary to alter the system of soil management or the cropping sequence which would otherwise be employed. The best weapon for fighting many insects is that of making conditions unnatural for them. This may be accomplished by crop rotation, by the time and depth of plowing, by the method of preparation of the soil for planting, by the time of planting, by the fertilizer practice, and by the means of disposal of the refuse from the crop.

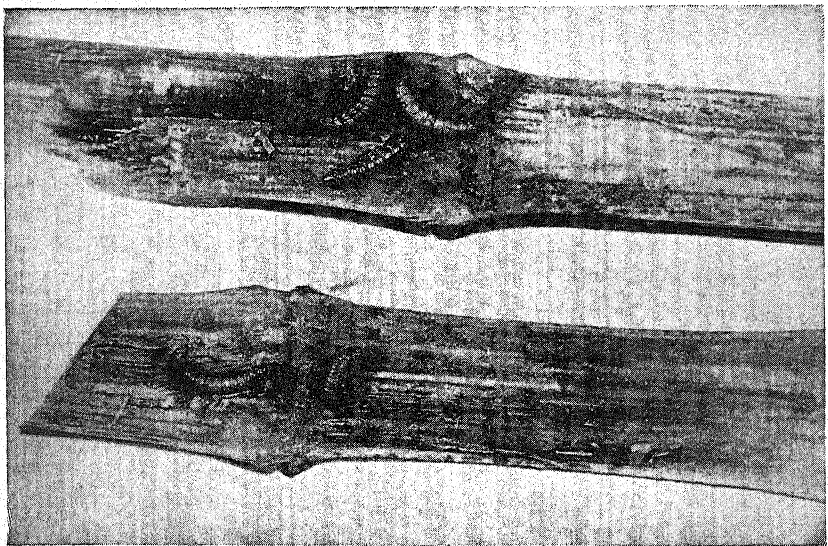

FIG. 35. Cornstalks infested with the European corn borer.

With the Hessian fly, rotation forces migration and subjects the frail insects to disasters en route. Delaying the seeding of winter wheat is an effective means of control. This requires that more fertilizer or manure be used in order that the wheat may make more rapid fall growth, once it has made a start. Cutworms, grubworms, and wireworms can be controlled in part by fall, winter, or early spring plowing which subjects them to freezing. Suggestions for the control of the corn borer include late planting and destruction, by burning, of all the crop refuse that is left on the field and cannot be readily buried by the plow. Of considerable interest in this connection is the fact that the cotton boll weevil forced the adoption of the principle of crop rotation and, indirectly, proved a benefit to the agriculture of the South.

Probably one of the most difficult problems in connection with the control of insects is that presented by permanent pastures in which rotation is not feasible. Osborne calls attention to this problem in a very impressive statement in which he indicates that "run-out" pastures may not be so much the result of soil exhaustion as of an accumulation of insects and other parasites of pasture grasses. It is possible that the marked effects resulting from the use of limestone and phosphate on pastures might be imitated, in part, by the use of some type of insecticide and fungicide to keep these parasites under control.

WEEDS AS NEGATIVE FACTORS

Weeds may also be considered parasites in the sense that they rob the crop plants of water and soil nutrients. They may also serve as hosts for diseases and insects which are injurious to crops. A notable example of this is the common barberry in relation to the black stem rust of wheat. Ordinarily, the more productive the soil the greater the difficulty with weed control. This is especially true on well-manured tracts of land that are used for market-garden purposes.

Weeds are particularly troublesome under such climatic conditions as obtain in certain northern European countries where the winter temperatures are not sufficiently low to kill them. The fall-seeded grains do not have the opportunity to get ahead of their competitors as they do under the climatic conditions of our northern states. Consequently, in Europe, hand weeding is commonly resorted to with the winter cereals. At Rothamsted, especial difficulty has been experienced on the continuous wheat plots in the control of the black bent grass. As a last resort, it was found necessary to keep the plots under fallow for a full year at two different periods in their history.

On the continuous corn, oats, and wheat plots of the Ohio Experiment Station Farm, no such difficulty has been experienced although the nature of the weeds varies with the crop.

Some special methods of weed control may be mentioned, such as taking advantage of the drought-resisting qualities of alfalfa in the irrigated regions of the West, using fertilizer in the hill to stimulate the more rapid growth of the crop rather than of the weeds and thus permitting earlier cultivation for their control, and regulating the reaction of the soil at a point that is suitable for a given crop plant but is fatal to weeds. This last method has been employed with especially good effect on putting greens and on lawns. On putting greens, bluegrass and white clover are considered weeds. These and all common weeds are eradicated by keeping the reaction of the soil below pH 5. This is usually accomplished by the use of sulfur or ammonium sulfate in the original preparation of the soil, and by heavy top dressings of sulfate of ammonia after the sod is established. At this reaction, bluegrass does not grow, but the bent grasses are not injured. These, together with the fescues and red top, constitute the grasses for acid soil conditions and for conditions in which it is desired to eliminate the weeds.

BACTERIA AS COMPETITORS OF PLANTS

In addition to the bacteria that are responsible for certain plant diseases, others that are less frequently mentioned merit consideration as negative factors in crop production. In the presence of large amounts of carbonaceous materials in the soil, the nitrate nitrogen may be utilized, as rapidly as it is produced, for the construction of protein in the bodies of microbiological forms of plant life. The plowing under of large amounts of straw, of heavy crops of non-leguminous green manures such as mature rye, or fresh strawy manure often gives unsatisfactory results. A variety of reasons can be given for the bad effects that are often noted in such cases, but the evidence indicates that the explanation lies in the utilization of available nitrogen and mineral nutrients by the abnormally large numbers of cellulose-decomposing bacteria that develop in the soil as a result of the use of these materials. If such substances are to be incorporated in the soil, it should be done as far in advance of planting the crop as is possible. If this is not feasible, one should then supply additional amounts of nitrogen and mineral elements in the form of fertilizers.

THE SOLUTION OF THE PROBLEM OF SOIL SANITATION

Except as effective and economical means for their control are known, the introduction of negative chemical and biological agents into the soil must be avoided. Once they are introduced, it is necessary to consider means by which they may be either eliminated or kept under control. Excessive quantities of soluble salts can be removed by irrigation and drainage where this is feasible, as in greenhouses and in portions of the alkali regions of the West. Methods for the precipitation of soluble constituents may be employed. These include the use of calcium sulfate as a remedy for alkali carbonates; the addition of superphosphate as a means of eliminating soluble aluminum; and the application of limestone to control the reaction of the soil at the point of lowest solubility of such elements as zinc, copper, manganese, and boron. It is also desirable that the soil contain considerable amounts of humus materials for their buffer effect on hydrogen and other ions that may be in the soil solution.

With negative biological agents, methods of prevention are usually of only temporary value. Once the organisms gain a foothold, the choice for control lies among the following methods: using heat, volatile antiseptics, and chemicals that leave no permanently harmful residue; growing disease-resistant strains or varieties of crops; and regulating the conditions in the soil so as to favor the host in preference to the parasite. The last-named method has many possibilities, among which the following merit consideration: the choice and method of use of fertilizers; the regulation of the reaction of the soil; the time and method of plowing and planting the crop; and the method of disposing of the plant residues. The losses resulting from failure to take advantage of these possibilities are often very serious.

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CHAPTER XX

CONTROLLING THE SOIL REACTION

Plants differ markedly in their soil-reaction requirements. Some of them, such as watermelons and blueberries, thrive on distinctly acid soils and are injured by liming. Some plants will grow on acid soils but respond markedly to the use of liming materials. Soybeans and corn may be cited as examples of such crops. Other plants can be grown satisfactorily only on soils whose reactions approach the neutral point. Cabbages and onions are crop plants of this class. Still other plants are able to tolerate considerable amounts of the alkali salts, including the carbonates of sodium and potassium. Asparagus and alfalfa may be mentioned in this connection.

In some instances the optimum reaction is that which meets the requirements for the metabolic processes within the plant, while in others consideration must be given to the solubilities of various soil constituents, which by reason of excess or deficiency limit the growth of the plant. Thus, as the soil reaction becomes more acid the quantity of soluble aluminum increases. Plants differ considerably in their tolerance for this element. If lime is added in such amounts as to bring the soil reaction approximately to the neutral point, the quantities of iron and manganese that remain in the soil solution may be inadequate for the needs of the plant. Examples of chlorosis of pineapple plants and beet plants from this cause have been noted. It has also been shown that, in some instances, the reaction at which the soil must be kept is primarily determined by the requirements of the microorganisms of the soil, some of which are beneficial and others injurious to crop plants. Thus, azotobacter do not thrive on soils which have a hydrogen-ion concentration lower than that indicated by pH 6; the clubroot of cabbage can be eliminated by making the soil distinctly alkaline in reaction; and the potato scab organism can be kept under control at about pH 5.

MATERIALS FOR REGULATING THE SOIL REACTION

Although certain farming practices are of value in controlling the soil reaction within reasonable limits, it becomes necessary at times to apply materials to the soil primarily for this purpose. The corrective agent employed to reduce the acidity of soils is usually calcium or magnesium in the oxide, hydrate, or carbonate form. These products ordinarily have their origin in limestones, which vary in their composition from almost pure calcium carbonate to nearly pure dolomite. The percentages of impurities in limestones vary within wide limits. Usually, limestone is not used for agricultural purposes when its impurities exceed 15 per cent. These impurities effect serious wear on the machinery of pulverization and add unnecessary weight to the product. In some localities there are large deposits of marl or chalk, which are used on the soil after being pulverized. These quite often contain from 75 to 95 per cent of calcium carbonate. A number of manufacturing processes have as by-products hydrated lime or carbonate of lime, which are useful for neutralizing acid soils. Blast-furnace slag is another by-product which has been shown to be of value for this purpose. Most of the lime in slag is present in silicate combinations.

Of the products that have been employed for making soils acid, three merit special mention. These are flowers of sulfur, aluminum sulfate, and sulfate of ammonia. The first of these is utilized by the sulfur-oxidizing bacteria in soils and is readily changed to sulfuric acid. This reacts with any carbonates that may be in the soil, or effects a decomposition of the silicate compounds with the production of sulfates. These may be largely sulfates of the alkalies or alkali earths, if the soil is alkaline, neutral, or only slightly acid in reaction; or iron and aluminum sulfates, if the soil is already distinctly acid in reaction. The use of commercial alum meets the requirements temporarily, with somewhat less danger of producing spots of excessive acidity such as may occur if the sulfur is not evenly distributed. It will also be recalled that sulfate of ammonia is used to good effect on putting greens or wherever the bent grasses or fescues are desired, because of its tendency when used in considerable amounts to make the soil acid. Similarly, other fertilizer materials have effects on the soil reaction, of which calcium cyanamide, basic slag, wood ashes, potassium carbonate, and nitrate of soda may be mentioned for their alkaline action, and ammonia salts and most organic ammoniates for their acid effects.

RELATIVE MERITS OF VARIOUS LIMING MATERIALS

There has been a considerable amount of discussion on the relative merits of the various liming materials. This has resulted in large part from the advertising and sales promotion of the several materials by those who have them to sell. Farmers in some localities are convinced that quicklime is preferable to pulverized limestone, while in other localities quite the opposite opinion prevails. Likewise, there are differences of opinion concerning the relative merits of hydrated lime, precipitated carbonate of lime, and limestone of different degrees of fineness and containing different ratios of calcium and magnesium. In general, the more intensive the agriculture, the greater the tendency to use the more finely pulverized products. Thus, in the New England states and in New Jersey, burned and hydrated lime are employed in the largest amounts; in Pennsylvania and New York, considerable quantities of the finely pulverized and sacked limestone and precipitated carbonate of lime are also used; in Ohio and Indiana, the coarser-ground limestone is employed; while in Illinois and farther west, limestone screenings are popular. These generalizations may be set aside from place to place by reason of the local production of some other liming material or the convenience of obtaining some by-product that is useful on acid soils.

It is a well-known fact that the elements calcium and magnesium have other functions in the soil and plant than those of simply neutralizing soil acids. If the soil is deficient in magnesium, a dolomitic limestone product is to be preferred over a high-calcium one. However, most soil and plant investigators agree that the primary purpose of liming the soil is to regulate the soil reaction to correct certain acid-soil conditions which interfere with the growth of plants. On this basis, the relative merits of the several liming materials can ordinarily be ascertained from their neutralizing capacities and their rates of solubility. If, for any reason, it seems desirable to develop considerable alkalinity in the soil, which is ordinarily not sought, then there is occasion for choice from among the oxide and hydrate forms.

RELATIVE NEUTRALIZING POWERS OF LIMING MATERIALS

The relative neutralizing capacities of equal weights of limestone and its products can be determined by measuring the amount of some

TABLE 109

NEUTRALIZING CAPACITIES OF EQUAL WEIGHTS OF LIMING MATERIAL

Assuming Chemically Pure Materials	Relative Capacity*
Calcium carbonate or limestone	100
Calcium oxide or burned lime	179
Calcium hydroxide or hydrated lime	135
Calcium magnesium carbonate or dolomite	108
Calcium magnesium oxide, magnesian lime	207
Calcium magnesium hydroxide, magnesian hydrated lime	151

* Neutralizing capacity of 100 pounds of pure material in comparison with an equal weight of calcium carbonate.

standard acid with which they will react. Assuming that the liming materials contain no impurities, their relative neutralizing powers may also be calculated from their formulas and are as indicated in Table 109, calcium carbonate at 100 being used as the basis for comparison.

As the table indicates, 100 pounds of burned lime are equivalent to 179 pounds of limestone in neutralizing capacity. Of particular interest is the fact that magnesian limestone, or dolomite, is more effective per unit of weight than is calcium carbonate. With impure materials, the neutralizing power in terms of calcium carbonate must be determined for each product. This provides a basis for calculating the relative values of the several materials, assuming uniformity with reference to their other properties. Perhaps a more useful method of presenting the information that is contained in the foregoing table is to recalculate these values in terms of the amount of material that must be applied to secure effects equivalent to those produced by 1 ton of calcium carbonate. The results of this calculation are shown in Table 110.

TABLE 110

EQUIVALENTS OF 1 TON OF CALCIUM CARBONATE

Assuming Chemically Pure Materials	Pounds
Calcium carbonate, or limestone	2000
Calcium oxide, or burned lime	1120
Calcium hydroxide, or hydrated lime	1480
Calcium magnesium carbonate, or dolomite	1850
Calcium magnesium oxide, or magnesian lime	965
Calcium magnesium hydroxide, or magnesian hydrated lime	1325

In proportion as the freight and hauling charges increase, the delivered cost of a ton equivalent of limestone is more likely to be less for the oxide or hydrate forms.

RELATIVE SOLUBILITIES OF LIMING MATERIALS

The solubilities of the various liming materials depend largely upon the chemical forms in which they exist and their rates of solution are determined by their fineness or state of division. The degree of solubility of certain liming materials is recorded in Table 111.

By reason of the greater solubilities of the magnesian limes, a higher degree of alkalinity can be developed by the use of these materials than by the application of high-calcium limes. The injurious results that have been noted occasionally from the use of heavy applications of burned lime made from dolomitic rock probably have their explanation in this fact. Similarly, the high solubility of sodium and potassium carbonates and hydroxides is responsible for their very injurious effects, as evidenced in black alkali spots.

TABLE 111

SOLUBILITIES OF LIMING MATERIALS IN CARBONATED WATER (MACINTIRE)

Chemically Pure Materials and Limestones	Grams per Liter*
Calcium oxide	1.0
Magnesium oxide	18.6
Calcium carbonate	1.1
Magnesium carbonate	14.1
High-calcium limestone	0.9
Dolomitic limestone	0.5

* In grams of calcium carbonate equivalent per liter of solution.

THE RATES OF SOLUTION OF LIMING MATERIALS

The rates at which the various forms of lime go into solution are determined by their solubilities and their states of division. The relative solubilities of the ordinary liming materials are in the following order: magnesium oxide or hydrate, high-calcium limestone, and dolomitic limestone, the most soluble product being placed first. The oxide, hydrate, and recarbonated forms of lime are in a very finely divided state, the particles being mere aggregates of molecules which adhere to each other in larger or smaller amounts, depending upon the conditions under which they are handled. With such materials, the rate of solution in the soil is quite rapid if distribution that is comparable with their state of fineness can be effected. With limestone and the various by-product slags, even though they are finely ground, the particles are much larger than those of the burned and recarbonated products. The rates of solution of the ground products of a given limestone bear a close relationship to their state of fineness.

Particles passing a *100-mesh screen,* or a screen having 10,000 openings to a square inch, expose much larger areas of surface to solution for a given weight of material than do those that are too large to pass a 10-mesh screen. For this reason, limestone products are ordinarily divided into four groups under the names of pulverized limestone, ground limestone, limestone meal, and limestone screenings, with somewhat arbitrary limitations as to screen requirements for each group. As the fineness increases, a point is finally reached at which it is not possible, in practice, to effect a distribution that is adequate to allow each particle of limestone to be in contact on all sides with the soil. Little or nothing is gained, therefore, by excessive fineness.

FINENESS TO WHICH LIMESTONE SHOULD BE GROUND

The fineness to which limestone should be ground is a matter of considerable controversy. It is not feasible to assemble and present any very large amount of the evidence that is available on this subject. Certain general principles may be stated that will be of use in making a choice among the various products that may be available for use. Fineness beyond 100-mesh material is not usually sought because of the expense. If maximum effects are desired within a few months of the time of application, the relative efficiencies of two products will be approximately in proportion to their percentage contents of 100-mesh material. Thus, if 50 per cent of one limestone product passes a 100-mesh screen and only 25 per cent of another is equally fine, 2 tons of the latter will be required to effect as much change in the soil reaction as 1 ton of the former. This is on the assumption that an equal percentage of both products passes a 10-mesh screen.

If the limestone is dolomitic, fineness of grinding is more essential than if it is a high-calcium stone. The finer the material, the more rapidly it will dissolve and the more quickly it will correct the acidity of the soil. Large amounts of very fine material may make the soil neutral or slightly alkaline, a condition that is undesirable for some crops and may cause chlorosis because of a resulting insufficiency of soluble iron and manganese in the soil solution. A product, all of which passes a 10-mesh screen and which contains all the intermediate sizes down to those that pass a 100-mesh screen, is perhaps as satisfactory as any since it supplies some very fine material for immediate needs and yet contains a considerable percentage of coarse particles that will become available somewhat more gradually. Very coarse material, particularly that of dolomitic nature, must be added in too large amounts to be economical, unless the quarry or railroad station is near at hand.

In general, as the hauling distance increases, screenings are replaced by limestone meal, and this in turn by ground limestone, then pulverized limestone, hydrated lime, and quicklime, in the order of decreasing quantities of material required to produce a given effect.

In Table 112 the data are of interest by reason of their bearing on the relation between fineness and efficiency of limestone as measured by crop yields. The limestone materials were applied at the rate of a little over 4½ tons an acre, which was 3 tons in excess of the estimated requirement of the soil, according to the Veitch test. The burned lime was applied in smaller but equivalent amounts. The liming materials were mixed with the soil in June, 1914. The soils that had been treated with burned lime and 100-mesh limestone showed no need for lime when tested in May, 1915. Similarly, the soils that had received 60–80 mesh limestone had their lime requirement satisfied in March, 1916, and those that had received the 20–40 mesh limestone, in March, 1917. The soil that had received the 8–12 mesh stone still showed two-thirds of its original lime requirement at the end of the three-year period. By this time, the soils that had received burned lime and ground limestone were beginning to show additional need for lime.

TABLE 112

Relative Yields* of Crops with Various Mesh Limestones (White)

Crops Grown	Burned Lime	100-Mesh Limestone	60–80 Mesh Limestone	20–40 Mesh Limestone	8–12 Mesh Limestone
Red clover†	422	406	199	150	128
Wheat†	127	132	118	114	106
Soybeans†	267	220	153	115	105
Hairy vetch†	339	294	255	191	110
Canada peas‡	157	178	156	117	110
Sweet clover‡	416	335	304	141	127
Crimson clover‡	172	160	150	115	106
Millet §	115	120	111	106	102
Lettuce §	100	91	87	38	1
Averages	235	215	170	121	99

* On basis of no-lime yield at 100, except in case of lettuce where highest yield was taken at 100, there being no crop on the unlimed soil.

†, ‡, and § indicate, respectively, years after liming in which crops were grown.

This and other evidence indicates that a product, all of which passes a 10-mesh screen and that contains all the finer materials 60 to 80 per cent of which usually will pass a 100-mesh screen, is perhaps as generally satisfactory as any.

IMPORTANCE OF OTHER CHARACTERISTICS OF LIMESTONES

Consideration may be given, not only to the percentage of magnesium carbonate and of impurity in limestone, but also to its porosity and its softness, in relation to the rate at which it is effective in the soil. The data in Table 113 were secured in a study of 10 limestones, chosen from various sources, which differed considerably in these several characteristics. The measure of their effectiveness was that of mixing them thoroughly with an acid Trumbull silt-loam soil and determining the residual carbonates at the end of a period of 35 days. This soil had a *p*H of 5.6 at the beginning of the test and was still acid in reaction at the end of the experiment. The limestone was applied at a rate of 10,000 pounds of calcium carbonate equivalent to 2 million pounds of soil.

An examination of the data reveals that there is no apparent relationship between the rate of solubility of limestones and any physical characteristic except fineness of division. As the percentage of magnesium carbonate increases, the rate of solution decreases. Some investigations indicate that a dolomitic limestone is a mixture of calcium carbonate and of calcium magnesium carbonate in the dolomitic ratio. The rate of solubility of the calcium carbonate is quite rapid; but after this has been dissolved there is a very marked decrease in the rate of solution of the limestone product, for only the dolomitic portion remains and this is only very slowly soluble. The higher the percentage of magnesium carbonate in the limestone, the greater the necessity of fine pulverization for immediate effect.

TABLE 113

SOME CHARACTERISTICS OF 10 DIFFERENT LIMESTONES (MORGAN)

$CaCO_3$, Per Cent	$MgCO_3$, Per Cent	Impurity, Per Cent	$CaCO_3$, Equivalent	Porosity, Per Cent	Abrasion* Per Cent	Residual Carbonate†	
						50-mesh	100-mesh
96.4	0.86	2.64	97.40	0.29	28.20	6920	4090
96.2	1.17	2.63	97.60	13.40	11.65	6640	3250
95.8	1.77	2.43	97.90	45.00	39.45	6090	3020
89.8	1.98	8.22	92.16	1.46	6.25	5570	2930
81.3	7.68	1.02	90.45	4.43	7.90	7270	4090
82.8	12.39	4.81	97.55	0.49	9.15	7640	4630
79.6	13.85	6.55	96.10	14.10	11.25	7390	4160
46.7	38.86	14.44	92.91	9.23	7.10	7950	5040
51.8	42.17	6.03	101.80	17.62	7.60	8130	5090
54.1	44.00	1.90	106.50	18.21	8.30	8290	5220

* Loss by abrasion in 2 hours — an indication of softness of the limestone.

† Residual carbonates remaining in Trumbull silt-loam acid soil at end of 35 days from an original application of 10,000 pounds of $CaCO_3$ equivalent.

RELATIVE MERITS OF BURNED LIME AND GROUND LIMESTONE

It has been noted in Table 112 that burned lime is somewhat more effective than even the finest limestone product for those crops that are particularly sensitive to acid soil conditions. It is also a well-known fact that the burned forms are more useful for the development of alkaline conditions where these are desired for any reason. Hydrated lime may be expected to give results equal to those secured with burned lime. The hydrated lime is often used for its convenience since it is shipped in sacks and can be procured in any town or city in which builders' supplies are sold. That this material is more rapidly effective than the usual 10-mesh limestone is indicated in Table 114.

TABLE 114

ACRE YIELDS* FROM USE OF HYDRATED LIME AND GROUND LIMESTONE (HARTWELL)

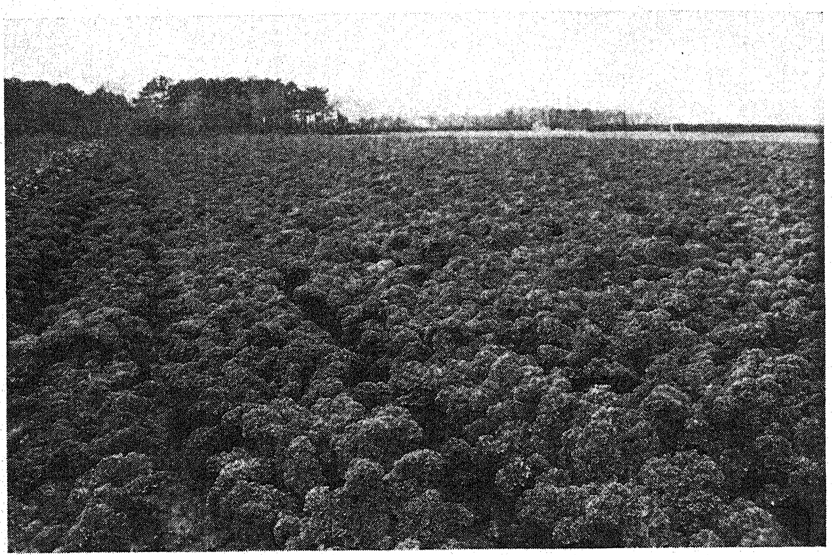
Periods	Hydrated Lime	80-mesh Limestone	10-mesh Limestone	No Lime
First Year:				
Alfalfa	35	38	27	24
Carrots	249	227	172	202
Beets	280	299	215	166
Barley hay	11	6	8	5
Five-year Averages:				
Alfalfa	42	33	36	22
Carrots	228	362	311	278
Beets	243	227	226	184
Barley hay	25	23	25	19

* Yields of hay in hundredweight and of root crops in bushels.

In the above test, 56 per cent of the 10-mesh product passed a screen with 80 meshes to the inch. Some of the 80-mesh material was separated from the 10-mesh product for a supplementary test. The liming materials were applied in amount equivalent to 2140 pounds of pure limestone to the acre. It is evident from the test that the hydrated lime is more immediately effective than is the 10-mesh ground limestone. For the five-year period, there is little choice between the hydrated lime and the limestone product all of which passed an 80-mesh screen. The liming materials were applied in amounts equivalent to approximately 1 ton of limestone to the acre. Heavier applications of liming materials resulted in material increases in yield over those produced on the plots receiving the above applications.

TIME AND METHOD OF APPLICATION OF LIMING MATERIALS

The effectiveness of liming materials is determined in large part by the extent of their distribution and subsequent mixing with the soil. If applied immediately after plowing, the lime is mixed with the top few inches of soil during subsequent tillage and while crops are being cultivated. If applied when the soil is being prepared for corn in a rotation with small grains and clover, the lime has plenty



Virginia Truck Station.

FIG. 36. A well-limed soil is required to grow a luxuriant crop of vegetables.

of time to become effective before the clover — the most sensitive crop of the rotation to acid soils — is seeded. Under such conditions a somewhat coarser product may be applied to advantage.

Usually, spring applications are objectionable from the point of view of the labor problem. For that reason, mid-winter, mid-summer, and fall applications of liming materials have been suggested. The experimental data in Table 115 indicate that, considered for a period of years, the time of application is not important. Even when the lime is applied on the clover sod, the yields are almost as satisfactory as when it is added to the newly plowed soil. The explanation probably lies

TABLE 115

ACRE INCREASES* FROM LIMESTONE APPLIED AT DIFFERENT TIMES (WILLIAMS)

Time of Application of Limestone	Corn, Bu.	Oats, Bu.	Wheat, Bu.	Clover, Cwt.
Land plowed for corn	15.0	4.5	4.7	13.7
Land plowed for wheat	15.5	3.5	4.4	14.7
After wheat harvest	13.6	3.9	5.6	11.8
On clover sod	15.1	4.0	6.3	12.1
One-fourth on each crop	11.4	4.2	6.3	13.3

* The 22-year average acre increases from finely ground limestone applied at rate of 2 tons every 4 years. Both the limed and unlimed land were treated with manure and superphosphate.

in the fact that the furrow slice is not turned completely over but is placed on edge, and subsequent tillage operations mix a considerable portion of the lime with the soil.

It seems from the above tests that, where the liming program is a regular feature of the scheme of soil management, the limestone can be applied at any convenient time. However, for heavy soils, particularly those whose lower horizons in the soil profile are strongly acid, late summer applications may be preferable. The drying out of the soil during hot weather tends to produce a porosity that permits more rapid penetration of the dissolved lime when the fall rains set in.

CONTROLLING THE SOIL REACTION FOR MARKET GARDENING

In the more intensive systems of market-garden farming, there is reason to believe that more attention should be paid to regulating the reaction of the soil to meet the needs of each crop grown. In general, the market gardener grows crops which do best on soils of relatively high pH (about 6.5). However, in growing those crops which are susceptible to clubroot, it is necessary to raise the soil pH still higher to effect their control. For potatoes, the soil pH must be considerably lower (about 5.2), otherwise scab becomes a troublesome factor. The dairy farmer needs alfalfa, and for this crop to grow satisfactorily the soil pH must be kept relatively high. On the other hand, such crops as oats, soybeans, and alsike clover do quite well on soils of relatively low pH. In the growing of flowers, the cost of controlling the soil reaction is a minor matter. Accordingly, special precautions are taken to make the soil acid for rhododendrons, azaleas, and mountain laurel, while great care is exercised in keeping the soil at a high pH for sweet alyssum, iris, and roses.

SUGGESTED SOIL pH LEVELS FOR PLANTS

While there is no exact pH level at which any given plant grows best, many plants are favored by controlling the soil pH on which they grow within relatively narrow limits. In Table 116 an attempt is made to classify some of the more common crop plants according to their pH tolerances or needs.

LIME REQUIRED TO RAISE SOIL TO GIVEN pH LEVEL

The amount of lime required to raise the pH of any soil to any given level depends upon the present pH and upon the exchange capacity of that soil. Its exchange capacity is determined by its content of colloidal clay and organic matter. A rough approximation

TABLE 116

SAFE SOIL pH'S FOR IMPORTANT CROP PLANTS

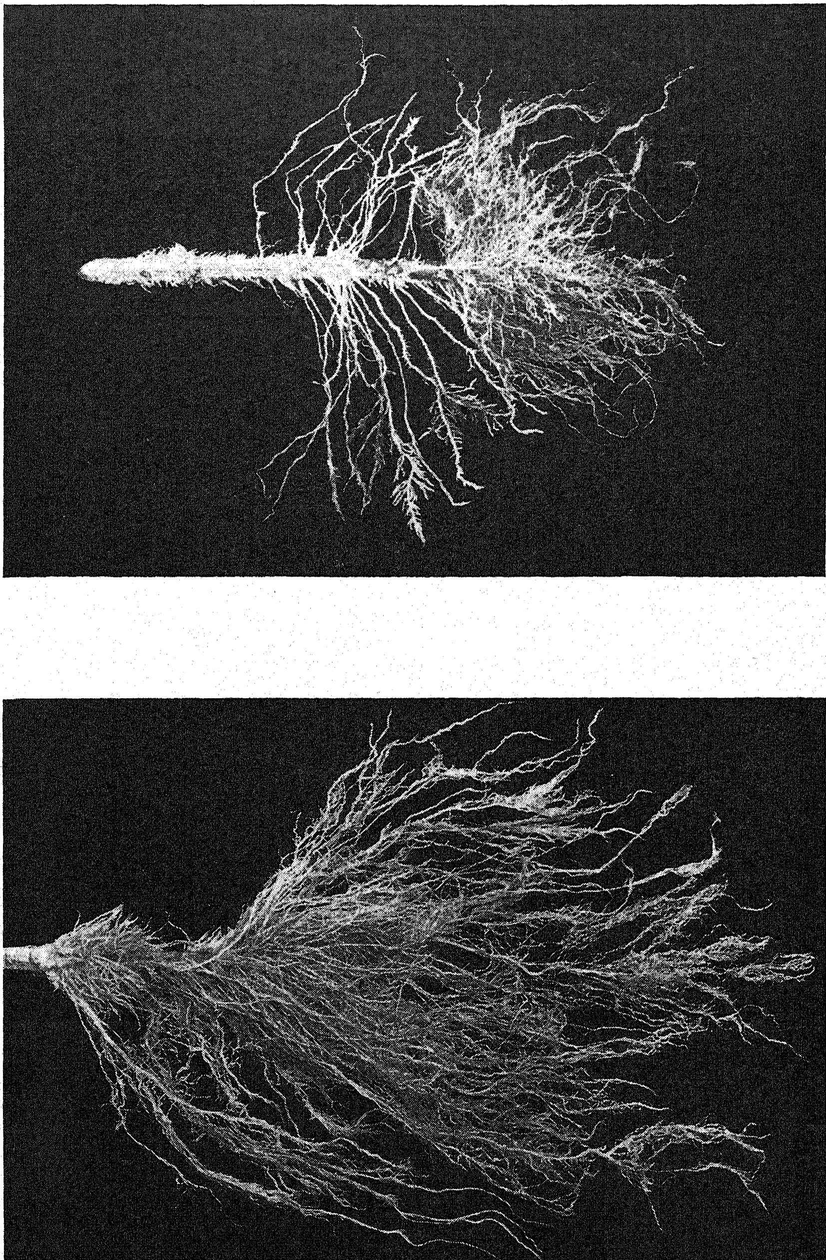
5.0	5.5	6.0	6.5
Beans	Alsike clover	Barley	Alfalfa
Bent grasses	Corn	Bluegrass	Asparagus
Cowpeas	Cotton	Cabbage	Beets
Millet	Crimson clover	Rape	Celery
Oats	Cucumbers	Red clover	Lettuce
Peanuts	Strawberries	Turnip	Onions
Potatoes	Tomatoes	Tobacco	Peppers
Rye	Timothy	Wheat	Spinach
Watermelons	Vetch	White clover	Sweet clover

of the exchange capacity of a soil, in milliequivalents per 100 grams of soil, is obtained by multiplying the percentage of clay by 0.57 and adding this to the product obtained by multiplying the percentage of nitrogen by 38.

For more exact estimates of the exchange capacities of soils, use is made of a solution of barium acetate. The soil is shaken up in this solution to effect an exchange of barium for the other cations. The supernatant liquid is decanted off and the process is repeated until the pH of the filtrate is the same as that of the original solution. The soil is then washed with a dilute solution of barium chloride, after which it is washed free of chlorides. This barium-saturated soil is then extracted with hydrochloric acid to remove the barium, the exact quantity of which is then determined by precipitation as barium sulfate.

By this and similar procedures it has been found that the exchange capacities of soils at pH 7 ordinarily lie between 2 and 20 milliequivalents per 100 grams of soil. A milliequivalent of calcium is 20 milligrams. To supply this amount of calcium would require the use of 50 milligrams of calcium carbonate or of pure limestone. Assuming that one had an H soil whose exchange capacity was 10 milliequivalents per 100 grams of soil, a total of 8000 pounds of limestone would be required to effect an 80 per cent exchange of calcium for hydrogen in 2 million pounds of that soil. A soil so supplied with calcium would have a pH of approximately 6.5.

However, the exchange complex of all field soils, no matter how acid they may be, is always partially saturated with calcium, magnesium, potassium, and sodium ions. What is required, therefore, is some means of estimating the amount of lime that is necessary to be applied to raise the present pH of the soil to that required for the



(a) (b)

Victor A. Tiedjens

FIG. 37. Calcium is highly essential for the development of good root systems. In its absence, roots are dwarfed and their tips are swollen. (a) Calcium. (b) No calcium.

crop to be grown. The quantities required for this have been experimentally determined for many soils. As a result, a few general suggestions can now be given as to the amounts of lime to apply to raise the pH of soils to the desired levels.

TABLE 117

LIMESTONE REQUIRED FOR 80 PER CENT SATURATION* OF EXCHANGE COMPLEX (MORGAN)

(Based on 2 Million Pounds, or Plow Depth, of Soil)

Exchange Capacity	Texture†	Present pH of the Soil			
		4.5	5.0	5.5	6.0
7	Sandy loam	3600	3000	2400	1800
9	Fine sandy loam	4500	3600	2900	2400
10	Loam	5200	4200	3300	2500
13	Silt loam	5800	4700	3700	2800
15	Clay loam	6300	5100	4000	3000

* To approximately pH 6.5.

† These calculations are based on the assumption that the soil contains a more or less average content of organic matter.

From these calculations, one is not only able to estimate the amount of limestone required to raise the pH's of soils from their present state to approximately 6.5, but also able to estimate the amounts needed to raise them to any other desired level. Thus, to raise the pH of a loam soil from 4.5 to 5 requires approximately 1000 pounds of limestone.

FIELD TESTS FOR LIME NEEDS OF SOILS

Of the many field tests which have been used over the years for estimating the lime needs of soils, the following are listed by reason of their interest in relation to the evolution of the methods now being employed: placing a piece of blue litmus paper inside a ball of moist soil and watching the rate and extent of the color change produced; shaking a sample of soil in a dilute solution of ammonium hydroxide and noting the extent to which the color of the solution was darkened by the dispersed humus; adding zinc sulfide to a soil suspension, applying heat, and noting the degree of darkening of a piece of moistened lead acetate paper which was held over the neck of the flask; testing the depth of color produced by shaking the soil in a dilute alcoholic solution of potassium thiocyanate; noting the color changes of mixed indicators whose endpoints are at various pH levels; and measuring the actual pH of the soil by the use of a portable potentiometer. The last two procedures are now widely employed both for field and laboratory testing of soils.

RELATIVE MERITS OF VARIOUS ACID-FORMING MATERIALS

Reference has previously been made to methods for overcoming the alkalinity of alkali soils. Since certain plants do not thrive on soils that contain even so slight an alkalinity as is produced by calcium carbonate, some means of overcoming this condition is needed. Sulfur, aluminum sulfate, and ammonium sulfate are employed for this purpose. In addition, for meeting the needs of acid-soil shrubs and flowers, the beds are acidified by the use of leaf mold, sawdust, pine needles, apple pomace, and even sour milk, and then are topdressed from time to time with aluminum sulfate or sulfate of ammonia.

SOLUTION OF THE PROBLEM OF CONTROLLING THE SOIL REACTION

In general, the problem is one of adjusting the soil reaction to approximately pH 6.5 and then maintaining it at this point by the addition of such further amounts of lime as are required. For especially sensitive crops, somewhat more lime may be required. For plants that are acid-loving, somewhat smaller amounts may be equally or more satisfactory. Ordinarily, if the soil solution becomes very acid in reaction, aluminum will be present in toxic concentrations; while if the soil is too close to the neutral point there may be a deficiency of iron, manganese, zinc, and boron, and perhaps also of aluminum if this is essential.

In the more humid areas, and particularly as the intensity of the agriculture increases, attention must be paid to the pH not only of the plowed soil but of the subsoil as well. This may call for plowing under extra lime and even placing some of it below the bottom of the furrow by the use of a chisel or subsoiling device. Such a procedure is especially important for deep-rooted crops like alfalfa. Once the lime needs of the entire soil profile are met, the problem of maintaining the pH at the proper point is a relatively simple one. However, the regular use of 1 or 2 tons of pulverized limestone, or its equivalent in other forms of lime, per acre every 4 to 8 years is now generally accepted as sound soil-management practice.

Under some circumstances it may be desirable to grow crops that are less sensitive to acid soil conditions. The farmers of the South have a system of cropping that seems to meet their requirements fairly satisfactorily in the growth of cotton, corn, cowpeas, rye, and oats, none of which is particularly sensitive to acid soil conditions. Similarly, it may be advisable under other circumstances to select those crops that are somewhat tolerant of acid soils and to follow such practices as will effect economy in the use of lime. In general, however, the most highly developed and profitable systems of agriculture in humid regions are based on the regular use of liming materials in such amounts as to permit the growing of the more sensitive crops. This seems to be particularly necessary for the intensive production of market-garden crops, many of which are very sensitive to acid soil conditions.

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CHAPTER XXI

NITROGEN FERTILIZERS

It has long been assumed that most of the nitrogen required to compensate for the losses of this element in the drainage water and from the sale of crops, as such or in the form of livestock and its products, will be secured from the air through the agency of the nitrogen-fixing bacteria, particularly those that are associated with nodule formation on the roots of legumes. This assumption had its origin at a time when vast acreages of very productive virgin soil were still available for extensive farming; when it was more profitable to farm new land extensively than to attempt to increase the acre yields of old land to very high levels by intensive methods; and when commercial nitrogen was so expensive that the value of the crop increase resulting from its use was less than the cost of the fertilizer carrying that element.

None of the premises on which this assumption was based now obtain, at least to the degree indicated above. The population of the United States has grown until it consumes practically as much food as the country produces. The land that remains to be brought under cultivation is limited in acreage and must, in large part, be reclaimed at considerable expense from deserts and swamps. The store of organic nitrogen that was contained in the virgin soils has been seriously depleted. Higher acre yields and more intensive farming are necessary both by reason of the relatively high cost of land and labor and the ever-enlarging requirements of a growing population. As a result of the perfection of methods for the production of synthetic nitrogen compounds, this element is available in large amounts and is much less expensive than formerly.

A smaller proportion of the crops that are being grown in the United States is being used for livestock purposes each year. A larger part of our crop produce is being consumed directly as food by man or is being employed in the production of articles that are necessary or useful for clothing, shelter, or the enjoyment of life. Products of the farm that formerly were of no value, except as they might be plowed under to improve the productivity of the soil, are now being used for a variety of other purposes. It is evident, therefore, that more dependence must be placed on fertilizers, and that commercial nitrogen must be used in increasing amounts, not only for market-garden and truck crops, but for the cereal, fiber, and hay crops as well.

NITROGEN ECONOMY IN GENERAL FARMING

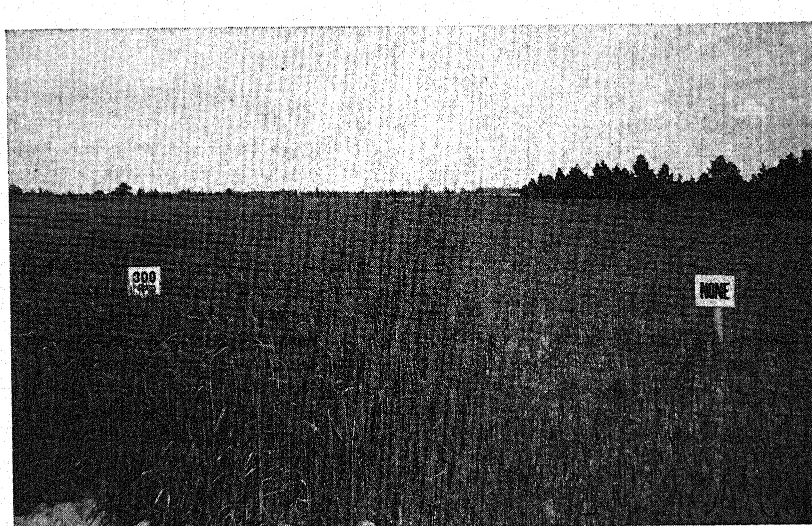
In a livestock system of farming, in which the crops that are produced on the farm are fed, and the manure, supplemented with superphosphate, is returned to the field without loss, there may be little need for commercial nitrogen. Likewise, in a grain system of farming, where sweet clover, alfalfa, or some other legume crop is grown successfully by the use of adequate amounts of phosphate and limestone, and this crop, as well as the stalks, straw, and other crop residues, is plowed under, fertilizer nitrogen may not be required. Yet it is rather generally true that soils that have been farmed under either livestock or grain systems of management, as they are usually practiced, are deficient in available nitrogen, and its application in readily available forms can be expected to produce considerable increases in yield.

The difficulty does not lie in the lack of efficiency of these systems of farming but in the failure of the farmer to meet one or more of their requirements. Experimental evidence shows that soils so managed can have their productivity renewed, in so far as available nitrogen is concerned, by legumes. The use of commercial nitrogen may be considered largely as an emergency measure by which the productive capacity of the soil can be more rapidly increased, after which the manure and clover programs can be put into effect and the further use of fertilizer nitrogen may no longer be profitable.

On the other hand, because of frequent changes of ownership or of tenants and because most farms produce certain acreages of crops that are outside either the livestock or grain systems of farming, what may be called the emergency need for commercial nitrogen is likely to continue to be widespread. Many general farms are producing large acreages of such specialized crops as cotton, tobacco, sugar beets, potatoes, hemp, and flax. The acre value of these crops is such that considerable expenditures for fertilizers may be justified. In general, it may be said that in proportion as it seems desirable to depart from the strictly livestock or grain systems of farming, as previously outlined, it becomes advisable to consider the possible source of profit in the use of nitrogen as well as the other elements that constitute mixed fertilizers. There is no sound argument against the using of supplemental fertilizer nitrogen in general farming if by so doing higher acre yields can be produced with a larger net return.

NITROGEN ECONOMY IN INTENSIVE FARMING

As long as city manure was abundant and cheap, the specialized-crop farmer made use of it in large amounts, not only as a source of nitrogen, but also for the reason that, when applied in liberal quantities, it served to improve the physical qualities of the soil. With the advent of the automobile, the amount of manure that was available was very materially decreased. Meanwhile the need for much larger acreages of market-garden, truck, and canning crops and fruits developed. It was found necessary to supplement the available manure with green manures and commercial fertilizers. On some farms the green-manure fertilizer system of soil management has been entirely substituted for the phosphated-manure program. The cost of fertilizer being only a relatively small part of the total acre expense of growing the more highly specialized crops, commercial nitrogen and other elements may be supplied in much larger amounts than they are removed in the crops. This is especially true by reason of the premium that is paid for early maturity and quality, both of which can be much improved by the proper use of fertilizers, and for which nitrogen is in many ways the most important constituent. Similarly, in the more intensive types of dairy farming, there is abundant opportunity to use fertilizer nitrogen as an aid to producing earlier, more, and better grass



The Barrett Company.

(a) (b)

Fig. 38. The yield of wheat on this field was more than doubled by topdressing with 300 pounds of nitrate of soda per acre. (a) Nitrate. (b) No nitrate.

for grazing, hay, and silage purposes. The possibilities for profitable increases in grass production by the use of nitrogen fertilizers on rotationally grazed pastures are far from being fully realized by dairy farmers.

SOURCES OF FERTILIZER NITROGEN

Both organic and inorganic carriers of nitrogen are available for fertilizer purposes. The former are usually by-products of some industrial process. The cotton, packing, fish, and tobacco industries and the garbage and sewage-disposal plants supply the major portion of the organic fertilizer materials. Considerable amounts of peat are also employed in the compounding of low-grade mixed fertilizers. The

TABLE 118

CONSUMPTION OF NITROGEN IN THE UNITED STATES (SHORT TONS OF N)
(Including Hawaii and Porto Rico)

	1913	1925	1938
Chemical Sources:			
Nitrate of soda	55,000	110,000	112,000
Sulfate of ammonia	30,000	82,000	104,000
Ammonia, urea, and nitrate liquors	.....	......	45,000
Calcium cyanamide	3,000	14,000	23,000
Calcium nitrate, urea, and derivatives	.....	1,360	23,000
Nitrogen in imported complete fertilizers	.....	......	1,000
Nitrate of potash and soda-potash	.....	......	5,000
Ammonium phosphates	.....	......	7,000
Total	88,000	207,360	320,000
Natural Organics:			
Cottonseed meal*	50,000	22,000	13,000
Packing house by-products†	30,000	3,200	4,000
Fish scrap	22,500	3,600	6,000
Guano	10,800	1,700	500
Garbage tankage	3,100	3,900	1,000
Rough ammoniates‡	15,000	13,500	2,000
Castor and tung pomace	1,400	1,500	1,000
Other nitrogenous material§	.....	6,900	14,000
Total	132,800	56,300	41,500
Grand total	220,800	263,660	361,500

* Includes that used by farmers direct.

† Includes tankage, dried blood, hoof and horn meal.

‡ Includes hair, leather scrap, wool waste, activated sludge, processed tankage, and nitrogen content of wet base goods.

§ Included under rough ammoniates in 1913.

inorganic carriers of nitrogen have their origin in natural salt deposits, in the coking of coal, and in synthetic nitrogen-fixation processes. The most important salt deposit is that of nitrate of soda in Chile. Large amounts of sulfate of ammonia are derived as a by-product in the production of coke and gas. Several varieties of salts, the nitrogen of which had its origin in the air, are now available for use. The table on page 256 gives the statistics of the consumption of nitrogenous materials in the United States for the years 1913, 1925, and 1938 calculated in terms of the element nitrogen.

Only a part of the tonnages listed in Table 118 were employed for fertilizer purposes. Nitrate of soda is used in large amounts in various industrial processes such as the manufacture of explosives; it is estimated that only 60 per cent of the nitrate of soda imported into this country is used for fertilizer purposes. High-grade tankage and cottonseed meal command a higher price as feeding stuffs than as fertilizers. The importations of carriers of nitrogen are offset in part by exportations of some of those that are produced in this country. It is, therefore, difficult to estimate the total amount of nitrogen that is used in fertilizers. The statistics are given primarily for the purpose of showing the variety of products that are available and the possible choice in the selection of materials to suit specific needs in the production and use of fertilizers.

SYNTHETIC NITROGEN FERTILIZERS

Over 60 per cent of the fertilizer nitrogen is now derived from the air. Most of the remainder is by-product sulfate of ammonia from beehive coke ovens and nitrate of soda from Chile. The original products in the synthesis of atmospheric nitrogen are calcium cyanamide, ammonia, and nitric acid. These are offered for sale either as such or in the form of ammonium sulfate, ammonium nitrate, ammonium phosphate, nitrate of soda, nitrate of lime, or urea.

The calcium cyanamide that is produced in America comes from Niagara Falls, Canada. The commercial product contains about 70 per cent calcium cyanamide ($CaCN_2$) and 25 per cent hydrated lime. It is made by passing nitrogen gas over hot calcium carbide. When this product is applied to the soil, it is hydrolyzed to urea and calcium hydroxide. A 100-pound bag of this material supplies as much lime as is contained in 100 pounds of limestone.

In the production of synthetic ammonium salts and urea, the starting point is ammonia that is produced by direct combination of nitrogen and hydrogen under suitable conditions of temperature and pressure in the presence of catalysts.

Nitric acid is produced either by direct combination of oxygen and nitrogen, at high temperatures, or by passing ammonia over a heated metallic catalyst where it burns to form nitric acid and water. The nitric acid is treated with soda-ash or limestone, and the resulting products, when evaporated to dryness, are the nitrate of soda and nitrate of lime of commerce. Most of the nitrate of lime on the market had its origin in Norway. The world's largest plant for the production of synthetic nitrate of soda is located at Hopewell, Virginia.

NITROGEN FERTILIZERS A BY-PRODUCT OF WAR

Every important world power, and many of the smaller countries as well, now have within their boundaries one or more large plants for the production of synthetic nitrogen compounds. Each nation feels the need of being independent from the rest of the world for nitrogen. In time of peace, it is needed as an agent in increasing crop yields; in time of war, for explosive purposes. The world's production of synthetic nitrogen before the beginning of the second World War was over 2 million metric tons of the element. The actual tonnage of nitrogen salts was probably 6 times that amount.

In time of war, manufacturing facilities for atmospheric nitrogen compounds are enormously increased and the total production is greatly enlarged. After the war is over, there is difficulty in finding an outlet for such large amounts of nitrogen. Accordingly, prices of nitrogen tend to drop below the cost of production. The cost of the plant having been written off during the war, or having been paid for by

TABLE 119

World Production and Consumption of Nitrogen* (In Metric Tons N)

Materials	1928–1929	1937–1938
Production:		
Chilean nitrate	490,000	224,000
By-product ammonia	427,000	460,000
Nitrate of lime	136,000	195,000
Calcium cyanamide	192,000	305,000
Synthetic ammonia	868,000	1,696,000
Total	2,113,000	2,880,000
Consumption:		
Agricultural	1,670,000	2,492,000
Industrial	202,000	380,000
Total	1,872,000	2,872,000

* From data compiled by the British Sulfate of Ammonia Federation.

governmental funds, only the out-of-pocket costs need to be considered. On this basis, nitrogen fertilizers become so cheap that many new uses are found for them which, under normal conditions of cost of production, would not have been economical.

CHARACTERISTICS OF CARRIERS OF NITROGEN

In defining the quality of a nitrogen fertilizer material, consideration must be given to at least five characteristics, viz.: its content of the element nitrogen; the rate at which this nitrogen becomes nitrified when applied to the soil; the effect of the nitrogen carrier on the soil reaction; the quality of the material as a conditioning agent in mixed fertilizers; and the extent to which the nitrogen contained in the product is retained by the soil against the leaching action of water. In Table 120 the various nitrogen carriers are rated in accordance with these characteristics. The choice from among them depends upon the conditions to be met and the relative costs of the nitrogen in the several materials.

TABLE 120

Comparative Values of Nitrogen Carriers As to Various Qualities

Material	Percentage of Nitrogen*	Nitrification of Nitrogen†	Acidity or Alkalinity‡	Retention by the Soil§	Quality for Condition‖
Ammonia (anhydrous)	82	90	Acid	Medium	Fair
Urea	46	90	Acid	Medium	Fair
Ammonium nitrate	35	95	Acid	Low	Fair
Ammonium chloride	26	90	Acid	Medium	Fair
Ammonium sulfate	21	90	Acid	Medium	Fair
Calcium cyanamide	22	90	Alkaline	Medium	Good
Calcium nitrate	17	100	Alkaline	Low	Poor
Sodium nitrate	16	100	Alkaline	Low	Fair
Ammonium phosphate	11	90	Acid	Medium	Good
Dried blood	10	80	Acid	High	Good
Animal tankage	6	70	Neutral	High	Good
Cottonseed meal	6	70	Acid	High	Good
Fish scrap	5	70	Acid	High	Good
Activated sludge	4	70	Acid	High	Good
Steamed bone	2	70	Alkaline	High	Good
Tobacco stems	2	70	Alkaline	High	Good
Garbage tankage	2	30	Alkaline	High	Good
Peat	2	20	Neutral	High	Good

* Minimum percentage of the element.
† Rate of change to the nitrate form in the soil.
‡ Tendency to leave an acid or alkaline residue in the soil.
§ Capacity of soil to retain until used by plants.
‖ For fertilizer-mixing purposes.

ACID EFFECTS OF NITROGEN FERTILIZERS

The one outstanding characteristic of all nitrogen materials, except the nitrates and calcium cyanamide, is their acid effect when applied to the soil. When the nitrogen of ammonia, urea, and by-product organics, as well as the nitrogen which is fixed by the nodule organisms, is nitrified by soil bacteria, the acid effects of the nitric acid produced during nitrification become apparent. However, part of the nitrogen is built up into proteins by plants and is thus removed from the soil without having had any harmful effect. In general, however, the recovery of fertilizer nitrogen in the immediate crop on which it is used does not exceed 50 per cent of the amount applied. The remaining 50 per cent may be used in part by soil microorganisms, in which event it is also stored in protein form. The permanently acidulating effects of an acid-forming nitrogen fertilizer are measured by the amount of nitrate which escapes in the drainage water. This varies from very small amounts in grass-covered soils to quite large quantities in soils under clean cultivation and in those soils that carry no growing plants during considerable portions of the year.

An added complication, as to the possible acid effects of nitrogen fertilizers, is involved in the use of a material like sulfate of ammonia. When the nitrogen of this compound is changed to nitrate and used by the crop or by soil microorganisms, the sulfuric acid is liberated, and this also has an acidulating effect on the soil.

This problem has been carefully studied by soil chemists who took into consideration not only the several carriers of nitrogen but those of phosphoric acid and potash as well; as a result, the following conclusions were reached with respect to the net effect of these fertilizer materials on the soil reaction:

Effect of Fertilizer Materials on Soil Reaction

1. One-half of the nitrogen is acid forming.
2. One-third of the phosphoric acid is acid forming.
3. In determining the net effect of any fertilizer material or mixture of materials on the soil, the following balance of elements is involved:

Acid-forming Elements	versus	*Base-forming Elements*
All sulfur		All calcium
All chlorine		All magnesium
$\frac{1}{3}$ of the phosphorus		All sodium
$\frac{1}{2}$ of the nitrogen		All potassium

A method was then developed for determining the "equivalent acidity or basicity" of fertilizers. It consists in titrating the excess of acidic or basic elements in a weighed sample of the fertilizer after it has been ignited to destroy any organic matter that may be present in it. This method has now been generally adopted. All states require an examination of all the fertilizers which are offered for sale within their boundaries. But some states require, in addition, a report on the acidity or basicity of these fertilizer materials and mixtures. As soon as such regulations went into effect, the fertilizer manufacturers found it necessary to formulate their mixtures so as to overcome their acidity. The usual procedure is to calculate the acid and alkaline values of the several materials that are employed in making up the mixtures and then to correct any excess acidity by adding dolomitic limestone. About the only exception to this occurs in the production of potato fertilizers. For potatoes, acid fertilizers are normally preferred as a means of keeping the scab-producing organisms under control.

Table 121 shows the acidity or basicity of the most commonly used nitrogen materials, as determined by the method of analysis which is now being employed by control chemists.

TABLE 121

Net Acidity or Net Basicity of Nitrogen Materials (Pierre)

Material	Nitrogen, Per Cent	Net Basicity as $CaCO_3$ per 100 Pounds of Material, Pounds	Net Acidity as $CaCO_3$ per 100 Pounds of Material, Pounds
Basic:			
Calcium cyanamide	22.0	62.3	....
Tankage (low-grade)	4.3	31.0	....
Nitrate of soda	16.0	28.8	....
Nitrate of potash	13.0	26.0	....
Nitrate of lime	15.0	20.3	....
Tobacco stems	2.8	12.0	....
Tankage (packing house)	6.0	9.9	....
Acidic:			
Anhydrous ammonia	82.2	....	148.0
Ammonium sulfate	20.5	....	110.0
Urea	46.6	....	84.0
Urea-ammonia liquor	45.5	....	82.0
Ammonium phosphate	11.0	....	55.0
Dried blood	13.0	....	22.6
Guano (Peruvian)	13.8	....	13.1
Cottonseed meal	6.7	....	9.4
Fish scrap	9.2	....	8.4

WET-PROCESSING OF ORGANIC AMMONIATES

Low-grade carriers of nitrogen are often processed by the use of sulfuric acid. The effect of the acid is to hydrolyze the proteins and to increase the rate at which their nitrogen becomes available in the soil. A comparison of the crop-producing qualities of processed and unprocessed organic carriers of nitrogen is shown in Table 122. It will be noted that their effectiveness has been greatly increased by acidulation.

TABLE 122

RELATIVE YIELDS* FROM RAW AND PROCESSED ORGANIC AMMONIATES (HARTWELL)

Material	Non-acidulated	Acidulated
Hair	41	80
Leather	29	100
Garbage tankage	16	10
Mixture of above three	61	105

* Relative yields of millet, oats, and buckwheat in comparison with those produced as a result of the use of dried blood valued at 100.

SECONDARY EFFECTS OF NITROGEN CARRIERS

Carriers of nitrogen contain other elements as well. The effect of these other elements, or of the compounds that are produced from them in the soil, on the crop and the soil must also be taken into consideration in determining the usefulness of the material. As the nitrate ion of sodium nitrate is taken up by the crop plant, the sodium ion is left behind in the soil and tends to produce an alkaline reaction. Under conditions of continued heavy use of nitrate of soda, the soil tends to become deflocculated and difficult to work. Nitrate of lime has a similar effect on the soil reaction but does not cause deflocculation. On the other hand, sulfate of ammonia leaves a residue of sulfuric acid and tends to increase the acidity of the soil. The relative desirability of these two types of nitrogen carriers is, therefore, determined in part by the reaction of the soil and the crops to be grown.

During hydrolysis to calcium hydroxide and urea, calcium cyanamide is toxic to plants. In using it, special precautions must be taken, particularly on sandy soils. Where used at the rate of 100 to 300 pounds per acre and for crops of which the seed are planted, the cyanamide should be applied ten days or two weeks in advance of planting and should be thoroughly mixed with the soil. When used as a top-dressing on grains or grasses or for fruit trees, it should be applied in late fall, or in the early spring before growth starts. For sidedressing cane or corn, it should be applied several weeks earlier than ammonia and nitrate forms of nitrogen. Calcium cyanamide has a neutralizing value equivalent to 75 per cent of that of hydrated lime.

The nitrogen of organic carriers becomes available in the soil at a rate that is determined largely by the recentness of origin of the material and its percentage content of this element. Substances such as garbage tankage and peat contain only very small percentages of nitrogen and large amounts of carbohydrate materials. In the process of decomposition in the soil, the nitrogen that is yielded up by these materials is utilized by the decomposing bacteria, with the result that little or none of it becomes available for crop plants. An excess of carbohydrate materials, such as straw or raw manure, when worked into the soil stimulates the multiplication of microorganisms to the point that they compete with crop plants, not only for the nitrogen that was added with these materials but for any available nitrogen in the soil, whatever may have been its source.

CONDITIONING PROPERTIES OF NITROGEN CARRIERS

While nitrogen fertilizers are often applied separately from other fertilizer materials, the major portion of the nitrogen is used in the form of mixtures containing phosphoric acid and potash as well. For this reason, it is necessary to consider the effect of the material on the condition of the resulting mixture. Many of the inorganic forms of nitrogen are objectionable either by reason of their hygroscopic nature or their tendency to react with other compounds with certain objectionable consequences. The nitrates, particularly nitrate of lime, are hygroscopic. Mixtures of sulfate of ammonia, superphosphate, and muriate of potash tend to "set" on standing. The hydrated lime in calcium cyanamide combines with the free acid in the superphosphate and effects a very marked improvement in the condition of a mixture. If used in considerable amounts, the hydrated lime reverts the soluble phosphates to an insoluble state, presumably through the formation of tricalcium phosphate. Urea tends to produce a sticky mixture with ordinary superphosphate. When used in concentrated mixtures with treble-superphosphate or ammonium phosphate, the working quality of the fertilizer seems to be entirely satisfactory.

For the above reasons, fertilizer producers prefer to use some form of organic nitrogen, such as tobacco stems, packing house refuse, cottonseed meal, garbage tankage, or peat. The nitrogen of some of these materials becomes available at a fairly rapid rate. The chief value of others lies in their conditioning effect. While it is highly desirable that the mixture be in good drilling condition, if this is secured at the expense of the availability of the nitrogen, little is gained by the use of the nitrogen carriers, since phosphate-potash mixtures of good condition can be made without the supplemental use of organic materials.

THE LEACHING QUALITIES OF NITROGEN CARRIERS

As previously indicated, the soil has very little capacity to adsorb the nitrate ion. If all the nitrogen is to be applied before or at the time of planting the seed or plants, the use of the nitrate form may not meet the requirements, particularly in regions of abundant rainfall and on soils that have a low exchange capacity and are very readily leached by water. Since, without question, nitrates are the most available forms of nitrogen and since plants take up a large part of their nitrogen during the early stages of their growth, nitrates may be more effective than other carriers of nitrogen even though some of the nitrogen supplied is wasted as a result of its being leached out of the soil. Evidently, the quantity of nitrogen to be added, the nature of the soil, the amount of rainfall, and the extent to which immediate availability is desirable, notwithstanding possible losses by leaching, must be taken into consideration in determining whether or not the nitrate form will meet the requirements. There is the further possibility of using only a part of the nitrogen at planting time and then giving the plants supplemental topdressings of nitrates later.

TESTS OF THE QUALITY OF ORGANIC NITROGEN

It is to be expected that low-analysis mixed fertilizers will contain a considerable part or all of their nitrogen in relatively insoluble or slowly available forms. Large amounts of peat and garbage tankage are used each year in fertilizer factories. While the nitrogen of these materials can be made more available by processing, frequently this is not done. It is necessary, therefore, to have some laboratory means of determining the quality of the organic nitrogen in fertilizers. Biological methods, in which the materials are mixed with soil and the rate at which nitrates are produced is determined, have been suggested. Such methods, unfortunately, are not well suited to ordinary laboratory routine. The method adopted as official by the Association of Official Agricultural Chemists is one that is known as the *permanganate method.* In this, the water-insoluble residue of a sample of the fertilizer is digested in a neutral or alkaline permanganate solution under certain standard conditions, after which the amount of nitrogen remaining in the undissolved residue is determined. The choice between the neutral and the alkaline solution depends upon the nature of the organic material. The method is an empirical one and in many ways is not satisfactory, but if intelligently applied it can be depended on to give a fairly reliable indication of the usefulness of the nitrogen in the organic materials contained in the fertilizer. Nitrates and ammonia salts are soluble in water and their amounts can readily be determined. From the tests of solubility in water and permanganate solutions, the control chemist can determine whether or not the nitrogen should be "passed."

USE OF MIXTURES OF NITROGEN CARRIERS

Considering the degree to which the carriers of nitrogen differ in their various characteristics, it seems logical to make use of a mixture of several of them rather than to apply only one form. This is particularly true where large amounts of fertilizers that are high in nitrogen are to be used, under conditions in which the soil is subject to considerable leaching, and in regions in which the seasonal distribution of the rainfall is quite irregular. Another fact to be considered is that organic ammoniates are especially useful in improving the condition of fertilizer mixtures, a most important factor in determining the evenness of their distribution in the soil.

Where high-grade organic ammoniates are available at prices that are little higher per pound of nitrogen than the cost of it in inorganic forms, the mixer usually uses about 200 pounds of an organic ammoniate in each ton of complete fertilizer for conditioning purposes. In their absence, fertilizer mixtures often become hard or lumpy and it is difficult to apply them evenly. An ideal mixture might well contain an organic ammoniate, an ammonium salt, and a nitrate, to meet both the immediate and the long-time requirements of the crop, assuming

TABLE 123

FORMULA FOR A 6-8-6* COMPLETE FERTILIZER

Material	Per Cent*	Pounds
Fish scrap or animal tankage (N)	8	250
Sulfate of ammonia (N)	20	300
Nitrate of soda (N)	16	250
Superphosphate (P_2O_5)	20	800
Muriate of potash (K_2O)	60	200
Dolomitic limestone	..	200†
Total		2000

* Percentage of nitrogen, phosphoric acid, and potash, respectively.

† This amount of limestone is nearly sufficient to neutralize all the acidity that would arise from the use of this mixture.

that all the fertilizer was applied at planting time. Such a mixture could be made according to the formula in Table 123.

An examination of the literature does not reveal adequate evidence in support of the use of the more expensive organic-inorganic mixtures except possibly for use on the sandier types of soil. Since it is now possible to produce mixtures of good drilling qualities from purely inorganic materials, the modern tendency is to dispense with the use of organics. However, there are always a number of low-grade organic materials which have little value for feeding purposes and which, therefore, can be purchased at low enough prices per unit of nitrogen to permit their use in fertilizer mixtures. The use of 100 to 200 pounds of such materials per ton of mixture serves as a further guarantee of good drillability.

In choosing experiments that are applicable in this connection, it must be admitted that those given are not necessarily applicable under all conditions. Nevertheless, the data are interesting as bearing on this question. The data in Table 124 are of considerable interest because they apply to the potato crop, a crop which thrives on acid soils. The average differences in yields resulting from the use of various mixtures of nitrate, ammonia, and organic forms of nitrogen are not sufficiently large to justify the choice of one instead of any of the others.

TABLE 124

ACRE YIELDS OF POTATOES AS DETERMINED BY FORMS OF NITROGEN (MAINE)

Carriers of Nitrogen*	1914	1915	1916	1917	1918	Average
Nitrate $\frac{2}{3}$, organics $\frac{1}{3}$	198	186	231	140	120	175
Sulfate $\frac{2}{3}$, organics $\frac{1}{3}$	182	198	231	142	142	179
Nitrate $\frac{1}{3}$, organics $\frac{1}{3}$, sulfate $\frac{1}{3}$	191	196	226	141	141	180
Nitrate $\frac{1}{3}$, organics $\frac{2}{3}$	198	183	231	128	128	176
Sulfate $\frac{1}{3}$, organics $\frac{2}{3}$	182	180	236	124	124	173

* The fertilizer employed was a 5–8–7 analysis and was applied each year at the rate of 1500 pounds an acre with the planter.

Many comparisons of mixtures containing various percentages of nitrate, ammonia, and organic forms of nitrogen have been made on cotton and corn in the southern states. The data in Table 125 have been chosen as representative of the results of such tests. It will be noted that both the sulfate of ammonia and the organics added to the crop-producing powers of the mixtures. However, the better showing which organics made over sulfate of ammonia can probably be ascribed to their being less acid. This advantage is readily overcome by adding enough dolomitic limestone to the sulfate of ammonia mixture to correct its extra acidity.

TABLE 125

SOURCES OF AMMONIA AS RELATED TO ACRE YIELDS OF COTTON* (SKINNER)

Nitrate	Sulfate	Organics	Yields	Relative
1	0	0	1256	100
0	1	0	1255	100
$\frac{1}{3}$	$\frac{2}{3}$	0	1358	108
$\frac{2}{3}$	$\frac{1}{3}$	0	1386	110
$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$B	1414	112
$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$C	1411	112
$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$F	1435	114
$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$T	1404	111
No fertilizer yield			788	...

* Experimental tests on sandy loam soils of three series. The data are averages for eight tests. B = dried blood; C = cottonseed meal; F = fish scrap; T = animal tankage.

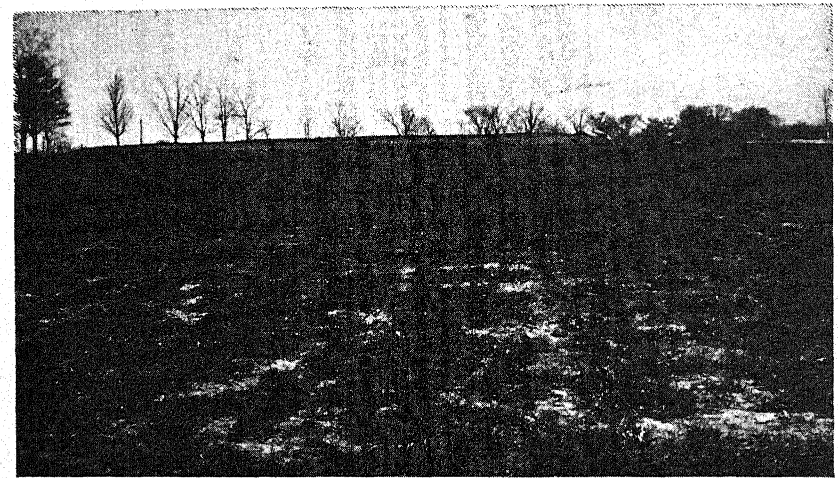
CONDITIONS FAVORING THE USE OF CERTAIN CARRIERS

There is evidence in favor of the use of sulfate of ammonia on those crops which grow best under acid soil conditions. Thus, on putting greens, for potatoes on scab-infested soil, and for blueberries and rhododendrons, sulfate of ammonia is generally recommended. In the growing of paddy rice, sulfate of ammonia is also preferred, partly because of its relation to the solubility of iron and partly because it is not subject to denitrification. Nitrate of soda is used in preference under conditions in which alkaline effects are desired, as for example in the control of clubroot of cabbage or for heavy applications on market-garden crops on soils that are naturally somewhat acid in reaction.

In the Connecticut Valley, tobacco growers have a decided preference for cottonseed meal by reason of the finer texture and better luster of the leaf that results from its use. Growers of white lilies often use soot as an aid in developing a better sheen on the blossoms. Most farmers prefer animal and green manures as supplements to inorganic fertilizers. This is particularly true for vegetable and truck crops. In the absence of an irrigation system for vegetable crops, there is evidence in favor of supplying the initial dressing of nitrogen largely in organic forms, in order that the nitrogen may become available according to the weather conditions, which also determine the rate of growth of the crop. This can be accomplished by applying inorganic nitrogen to cover crops and plowing them under.

SOME SPECIAL USES FOR NITROGEN FERTILIZERS

It seems desirable to consider some of the special uses to which nitrogen fertilizers may be put. Among these may be mentioned their particular value on lawns, pastures, and timothy meadows; for the production of high-protein wheat; and for increasing the yield of fruit trees, grape vines, and small fruits. In each of these uses there seems



O. J. Noer, Wis. Agr. Exp. Sta.

FIG. 39. *No fertilizer.*

FIG. 40. *One ton of 5–8–6 fertilizer per acre.*

High nitrogen fertilizers are especially important in the growing of grasses. Photographs of fairway of golf course.

to be a greater need for supplemental nitrogen than for any other fertilizer element, although at certain times there may be a choice between supplying this nitrogen as fertilizer or through the growth of legumes. If for the latter purpose, phosphate and potash fertilizers may be used instead, as indirect means of securing the necessary nitrogen through stimulation of the nitrogen-fixation processes.

Topdressings of some readily available carrier of nitrogen tend to keep a lawn covered with a satisfactory growth of grass. In bluegrass lawns in which white clover is not objectionable, phosphate and potash fertilizers may be used to advantage as a supplement to the nitrogen fertilizers. On putting greens or on lawns that are covered with bent grass, from which it is desired to eliminate clover and weeds, the use of sulfate of ammonia as a topdressing meets most of the requirements. While applications of lime, phosphate, and potash will be required from time to time, the predominating need is for frequent application of a carrier of nitrogen that leaves an acid residue.

On pastures, the common practice is to use heavy dressings of limestone and of phosphate and potash fertilizers and to depend upon white clover to accumulate the necessary nitrogen. Frequently this meets the requirements quite satisfactorily. However, it is usually possible to increase the yield of grass further by the supplemental use of nitrogen fertilizers. This is particularly true for early grazing. Many farmers set aside one field for this purpose, the acreage in this field being about one-sixth that of the number of cows in the herd. This nitrogen-fertilized grass gets the first grazing and is rotationally

TABLE 126

Effect of Ammoniates on Percentage of Protein in Crops (Phelps)

Crop	No Nitrogen*	25 Lb. Nitrogen*	75 Lb. Nitrogen*
Corn, grain	10.9	11.3	12.1
Oats, grain	15.1	15.4	16.3
Corn stover	6.2	6.6	7.6
Oat straw	5.3	4.7	6.0
Hungarian grass	8.9	9.1	12.7
Timothy	7.8	8.5	11.3
Orchard grass	8.4	11.1	14.7
Meadow fescue	7.8	10.4	14.1
Tall oat grass	7.4	10.7	13.7
Cowpea vines	20.1	18.9	20.0
Soybean seed	40.2	40.1	42.4

* Carriers of phosphoric acid and potash were applied in the same amounts in every case.

Note: Early applications of nitrogen have their greatest effect on yield of hay, while later applications — 3 weeks ahead of harvest — tend more to increase the protein content.

grazed for the remainder of the season. Nitrogen-fertilized grass must be closely and regularly grazed to prevent its crowding out the clover.

In the northeastern part of the United States is an extensive hay and pasture belt in which the climatic and soil conditions are much more favorable for timothy and other grasses than they are for the hay and pasture legumes. Some very striking effects have been secured by topdressing the meadows with nitrate of soda or sulfate of ammonia. A Connecticut experiment, data from which are recorded in Table 126, is of value in showing the possibilities of increasing the protein content of plants by the use of nitrogen fertilizers. Another, made at the Delaware Station, is of especial interest since the test was made on poor soil and the experiment had been in progress without interruption for nine years when the report was made. The land was prepared and seeded to red and alsike clovers and timothy at the rate of 8, 4, and 10 pounds an acre each, respectively. An application of 1200 pounds of hydrated lime was made to the soil at the time of seeding. No fertilizers other than those carrying the element nitrogen were applied.

TABLE 127

ACRE YIELDS* OF HAY IN TOPDRESSING EXPERIMENT (SCHUSTER)

Year	No Nitrogen	Nitrate of Soda†	Ammonium Sulfate†
1913	37.81	46.58	47.53
1914	37.81	46.77	48.75
1915	54.13	69.78	70.54
1916	37.63	50.73	46.21
1917	28.48	45.64	41.11
1918	35.64	51.86	52.43
1919	23.76	32.82	31.78
1920	37.25	36.02	38.10
1921	18.39	32.44	28.76
Average	34.54	45.85	45.02

* Yields, in cwt. an acre.

† The nitrate of soda was applied at the rate of 300 pounds and the sulfate of ammonia at 150 pounds an acre annually.

The quality of hard wheat is correlated with its content of protein. A premium of more than 10 cents a bushel is paid on the Kansas City market for wheat that can be classed as " choice dark red " over that designated as the " best yellow hard." The protein content of wheat can be increased by the growth of leguminous crops preceding the wheat crop or by topdressing the wheat with readily available nitrogen fertilizers.

Market gardeners and truck farmers have long been familiar with the advantages in the use of highly available carriers of nitrogen as a means of hastening the rate of growth and improving the succulence of vegetables. In many instances, orchardists have found that top-dressings of soluble nitrogen fertilizers increase the fruitfulness of trees, grape vines, and small fruits. This is especially true in orchards in which the trees are grown under the grass-sod system. The grass tends to repress nitrification and to utilize most of the available nitrogen. The data in Table 128 are of considerable interest in this connection for they show the effectiveness of nitrogen fertilizers on the fruitfulness of apple trees.

TABLE 128

POUNDS OF APPLES PER TREE WITH AND WITHOUT NITROGEN* (BALLOU)

Soil Type	Sod System		Tillage — Cover Crop	
	Check	Nitrogen	Check	Nitrogen
Clermont silt loam	87	236	81	257
Miami silt loam	96	147	165	158

* Each tree received approximately 5 pounds of nitrate of soda, or its equivalent in sulfate of ammonia.

Superphosphate was used over the entire orchards. The yields are averages for three-year periods.

THE PRINCIPLE OF THE NITROGEN-CARBOHYDRATE RATIO

The behavior of a plant with reference to its growth and reproduction seems to depend to a considerable extent on the relative proportions of nitrogen and carbohydrates that are available for its use. An abundance of nitrates, under conditions that are also very favorable for carbohydrate synthesis, tends to produce very rapid vegetative growth. If fruitfulness is desired, as in the case of tomato plants and apple trees, there must be sufficient excess of carbohydrates to permit of an accumulation of the latter at the expense of possible vegetative growth. Under conditions in which the supply of nitrogen is relatively low, there may be very little vegetative growth of the above-ground portion of the plants, but extensive root development may take place. It is thus evident that it is desirable to control the supply of nitrogen with reference to the ability of the plant to manufacture carbohydrate materials from carbon dioxide and water. The nature of the crop, the season of the year during which it is grown, and part of it which is of commercial value must be considered in determining upon a policy as to the use of nitrogen fertilizers.

USE OF NITROGEN FERTILIZERS AS FEEDS

Urea and ammonium carbonate have been found useful as partial substitutes for protein in the feed of calves. The nitrogen is utilized in the production of protein by the bacteria which inhabit the rumen. This protein is subsequently digested in the fourth stomach and the intestines. Most efficient utilization of such nitrogen occurs when the feed contains soluble sugars. It would appear that these simple nitrogen compounds would have important possibilities as supplements to grass silage or to concentrates to which molasses has been added.

RÉSUMÉ CONCERNING THE USE OF NITROGEN FERTILIZERS

Nitrogen can be secured from the air through the agency of nitrogen-fixing bacteria. In the livestock system of farming, much of the nitrogen of the feeds may be recovered in the manure and returned to the field. In the grain system of farming, the legume crop may often be plowed under to advantage. Very little commercial nitrogen may be required under such systems of soil management. In specialized types of farming, the use of considerable amounts of readily available nitrogen is usually found to be profitable, even in addition to any manure that may be available or any legume crops that may be used for green-manuring purposes. The amount of fertilizer nitrogen that can be used to advantage is determined by the system of farming, the acre value of the crops, and the cost of the nitrogen. All these are variables that change from time to time. It seems worthwhile for all classes of farmers to consider nitrogen as a possible source of profit and to be prepared to make use of it when such an opportunity arises. The choice of nitrogen materials is determined by the nature of the climate, the crop, and the soil. Most of the inorganic forms carry readily available nitrogen. The organic forms are somewhat more slowly available but are not so subject to leaching. When the percentage of nitrogen in the material is very low, as is true of garbage tankage and peat, it is necessary to resort to treatment with sulfuric acid to make the nitrogen available.

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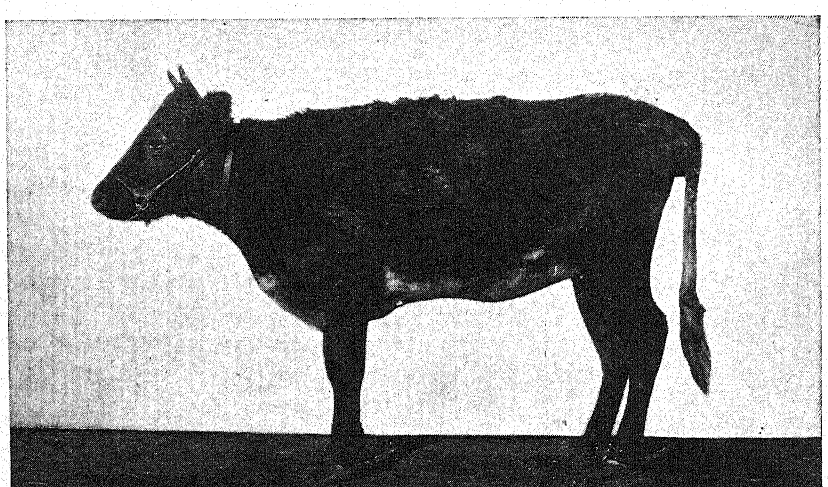
CHAPTER XXII

PHOSPHORIC ACID FERTILIZERS

Van Hise writes:

> The problem of the conservation of our phosphates is the most crucial, the most important, the most far-reaching with reference to the future of this nation of any of the problems of conservation.

The explanation of the importance of the phosphate deposits is found in the fact that phosphorus is an essential constituent of plant and animal life; the quantity of it in the average soil is relatively small; it is being removed from the farm in considerable amounts in cereal grains and in the bones of animals, including man; and there is no atmospheric supply of this element on which plants can draw. It is a matter of common experience that soils become deficient in available phosphorus early in their agricultural history. It is seldom that the crops fail to respond with increased yields when soluble phosphates are applied to soils that have been under cultivation for twenty-five years or more.



C. H. Eckles, Minn. Agr. Exp. Sta.

FIG. 41. A cow suffering from a lack of phosphorus on a farm in an area of phosphorus-deficient soil.

PHOSPHORUS ECONOMY IN GENERAL FARMING

While the livestock system of farming, in its best-developed forms, permits of maintaining the nitrogen content of the soil at a high level without the supplemental use of this element in the form of fertilizers, this is not the case with phosphorus. The higher the yields, the greater the acreages of legumes, the larger the sales of livestock or its products from the farm, the more rapid is the depletion of the phosphorus content of the soil. This fact is so generally known that it is the usual practice of livestock farmers to re-enforce their manure with phosphate or to apply this material separately when the crops are planted.

Similarly, in the grain system of farming, the phosphorus content of the soil is rapidly reduced to the point where the lack of this element becomes a limiting factor in crop growth. This is because phosphorus tends to concentrate in the grain whereas the other mineral nutrients are contained in larger amounts in the stalks and roots of plants, which are returned to the soil. Grain farmers, as well as livestock farmers, early in the history of any newly developed farming area, find it necessary to employ some carrier of phosphorus for fertilizer purposes. In fact, the only fertilizer that is used by a large percentage of the general farmers of the United States is superphosphate, a product whose value lies for the most part in its content of available phosphoric acid.

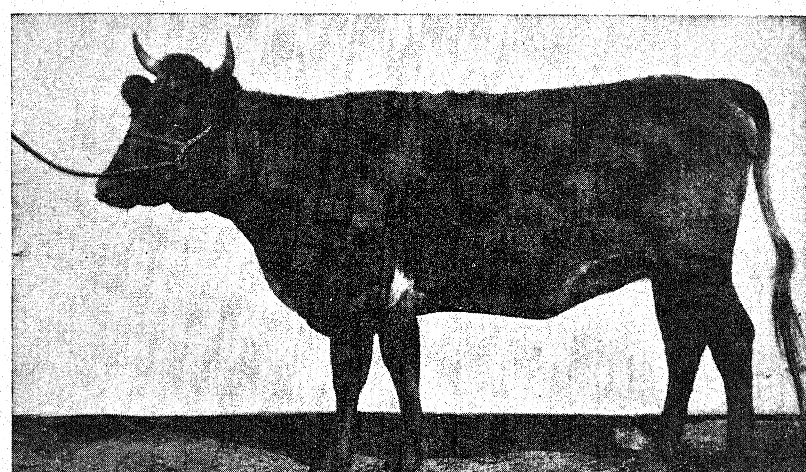


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FIG. 42. The same cow as in Fig. 41, 300 days later. During this interval she received a supplement of tricalcium phosphate, and gained 333 pounds.

PHOSPHORUS ECONOMY IN INTENSIVE FARMING

Most of the crops that are produced in intensive farming do not require such large amounts of phosphorus as do the grain crops, and their sale from the farm does not result in such serious losses of this element. On the other hand, phosphorus is an essential constituent of all plants. Since in the growing of specialized crops the acre yields can profitably be maintained at a high level, phosphorus, as well as the other essential elements, is supplied in liberal quantities and in such amounts as will give a proper balance to the nutrient solution in which the roots are bathed in the soil. The fundamental difference between the problem of the use of phosphates in general farming and in intensive farming lies in the fact that in general farming phosphorus is, as a rule, the predominating element in the fertilizer, while in intensive farming certain other nutrient elements are of equal or greater importance.

SOURCES OF FERTILIZER PHOSPHORUS

Before the discovery of deposits of phosphate rock, the only known source of phosphorus in commercial quantities was bones. These were in such demand that Liebig, in a scathing denunciation of the English, accused them of robbing the battlefields of Europe in order to secure the necessary bones with which to renew their depleted soils. The finding of the Florida phosphate fields in 1837 was, therefore, a matter of

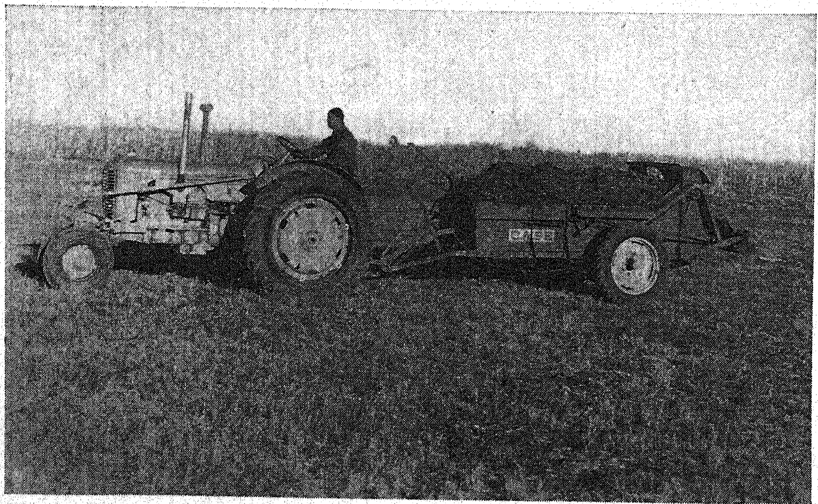

FIG. 43. Manure should be re-enforced with phosphate. Many farmers apply 50 pounds of superphosphate over each load before it is hauled to the field.

widespread interest and proved the solution of a problem that had been threatening world peace. While considerable amounts of bones are available from packing houses for fertilizer purposes, they supply only a relatively small amount of the total phosphorus that is applied to soils. Their use permits the return to the soil of part of the phosphorus that is removed from it in crops; but, as the population increases, a larger percentage of the total phosphorus content of plants is tied up in the bones of human beings, of which little is recovered to the cropped soil. A large amount of this element is also irretrievably lost in the sewage and garbage of cities. The latter losses will be considerably reduced when modern methods of sewage and garbage disposal are put into effect in the large cities.

Another source of phosphorus is the basic slag that is derived from the refining of iron ores, which are relatively high in their content of this element. This product has long enjoyed considerable popularity in European countries, partly because it constitutes their most im-

TABLE 129

STATISTICS OF PHOSPHATE ROCK IN THE UNITED STATES AND ESTIMATED PRODUCTION OF SUPERPHOSPHATE

Phosphate Rock, Tons of 2240 Lb.					Superphosphate, Tons of 2000 Lb.
Year	Marketed Production	Exports	Imports	Consumed in United States and Possessions	Estimated Production
1910	2,654,000	1,083,000	21,000	1,593,000	2,876,000
1915	1,835,000	253,000	5,000	1,587,000	2,776,000
1920	4,103,000	1,069,000	100	3,034,000	5,351,000
1925	3,481,000	870,000	2,000	2,614,000	4,659,000
1826	3,209,000	748,000	17,000	2,478,000	4,367,000
1927	3,170,000	918,000	28,000	2,280,000	3,847,000
1928	3,501,000	898,000	45,000	2,648,000	4,592,000
1929	3,761,000	1,142,000	44,000	2,663,000	4,598,000
1930	3,926,000	1,225,000	32,000	2,733,000	4,559,000
1931	2,534,000	951,000	13,000	1,597,000	2,508,000
1932	1,706,000	613,000	12,000	1,106,000	1,636,000
1933	2,490,000	829,000	7,000	1,668,000	2,671,000
1934	2,834,000	993,000	0	1,841,000	2,851,000
1935	3,042,000	1,104,000	3,000	1,941,000	3,102,000
1936	3,351,000	1,208,000	3,000	2,164,000	3,321,000
1937	3,956,000	1,052,000	13,000	2,916,000	4,411,000

portant source of phosphorus, but also because it carries a considerable amount of calcium in a form that is useful for neutralizing acids in the soil. A ton of basic slag has a neutralizing value equivalent to approximately half a ton of ground limestone. Likewise, bone meal and phosphate rock contain some calcium in the carbonate form, which is of value when used on acid soils.

By far the most important source of phosphorus is phosphate rock, which is now known to exist in large amounts in various portions of the world. Of these various deposits, those of the United States are probably the most extensive. These deposits are found in Florida, Tennessee, and the Carolinas, and in enormous quantities in Utah, Wyoming, Idaho, and Montana. While the rock can be used as such when finely pulverized, it has found its largest use in the form of acid phosphate, a product resulting from the action of sulfuric acid on phosphate rock. Table 129 gives the statistics of the production of phosphate rock and of superphosphate for the United States for the years 1910 to 1937, inclusive.

There being no need for very large quantities of phosphates, except for fertilizer purposes, the statistics show the approximate tonnages of them that were applied to the soil. Not over 2 or 3 per cent of the raw phosphate rock that is mined is used as such, although most of the other carriers of phosphorus are added to the soil in their natural state except that they are subjected to mechanical processes of pulverization before being used as fertilizers. Considerable amounts of animal

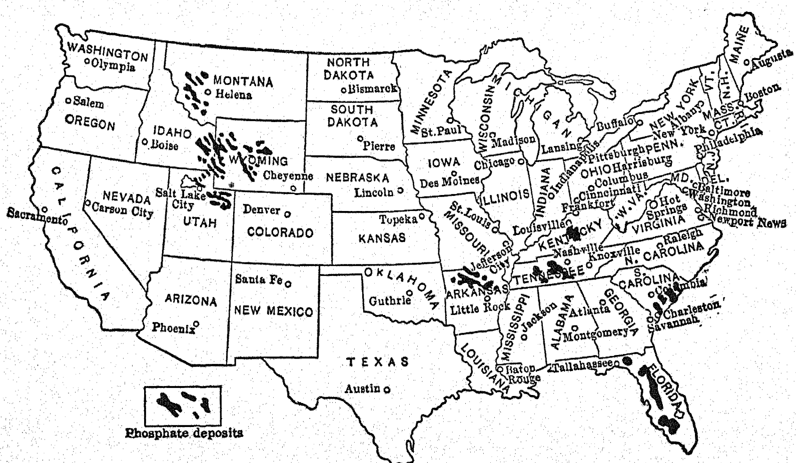

FIG. 44. Deposits of phosphate rock are looked upon as one of the most important natural resources of any nation.

tankage, fish scrap, and bone are used in the compounding of stock feeds.

PHOSPHATE-ROCK DEPOSITS IN THE UNITED STATES

By reason of the importance of the phosphate deposits as related to our national welfare from the point of view of food production, it seems desirable to consider the available supplies of this rock and its distribution. Table 130 gives the estimated quantities that are available in long tons in the several states in which the phosphate deposits are found.

TABLE 130

Tons* of Phosphate Rock Available in the United States (Mansfield)

Eastern Field	Tons	Western Field	Tons
Florida	5,096,000,000	Idaho	5,738,000,000
Tennessee	194,000,000	Utah	1,741,000,000
Arkansas	20,000,000	Montana	391,000,000
South Carolina	9,000,000	Wyoming	115,000,000
Kentucky	1,000,000	Grand Total	13,305,000,000

* Long tons of 2240 pounds each.

While the United States leads in the production of phosphate rock, its exports are considerably less than formerly because of the discovery of enormous deposits of the rock in Algeria, Morocco, Tunis, and other portions of northern Africa and because of other large amounts in Ocean and Nauru Islands in the Pacific Ocean. There are important phosphate deposits in various other parts of the world, so that abundant supplies are available for meeting the world's needs for several centuries. In addition, England and Germany are producing large amounts of basic slag, the annual production in Germany amounting to over 1 million tons.

CHARACTERISTICS OF VARIOUS CARRIERS OF PHOSPHORUS

The term quality, as applied to phosphates, is mostly a matter of solubility. Bone is largely tricalcium phosphate. It is very porous, and its pores contain considerable amounts of nitrogenous organic matter that provides food for bacteria which aid in effecting its solution. The rate at which its phosphorus becomes available to plants is much more rapid than that of phosphate rock. The rock is very compact and carries its phosphorus in the highly insoluble form of calcium fluorphosphate $[Ca_{10}F_2(PO_4)_6]$. However, if this material is heated to a temperature of 1400° C. in the presence of water vapor its fluorine is dissociated, and a product carrying 30 to 35 per cent of available phosphoric acid is obtained. Basic slag, a by-product of the steel industry, carries its phosphorus in the form of calcium silicate phosphate, plus some free lime. Its lime is of considerable value on acid soils. The combined effects of its phosphorus and lime are such that basic slag often produces results which are equal, pound for pound, to those obtained by the use of superphosphate carrying the same percentage of phosphoric acid.

THE MANUFACTURE OF SUPERPHOSPHATE

To increase the solubility of phosphate rock, one can resort to the use of either high temperatures or sulfuric acid, both of which accomplish much the same purpose. Treatment with sulfuric acid has been shown to be so effective that it is generally employed with the resulting production of superphosphate. In this process, approximately equal weights of phosphate rock and commercial sulfuric acid are used. The product of this reaction, after its curing and subsequent pulverization, constitutes the ordinary 14 to 20 per cent superphosphate of the fertilizer trade, the percentage depending upon the purity of the original rock. The action of the sulfuric acid results in the formation of calcium sulfate, with the consequent substitution of hydrogen for calcium in the phosphate molecule. Thus, superphosphate is largely a mixture of calcium sulfate and of the monocalcium and dicalcium phosphates. A 16 per cent superphosphate is one in which the phosphoric acid anhydride (P_2O_5), commonly called phosphoric acid, in the monocalcium and dicalcium phosphate forms amounts to 16 per cent by weight of the product. The monocalcium phosphate is soluble in water. The dicalcium phosphate will dissolve in weak acid solutions. The phosphate rock, which escaped the action of the sulfuric acid, must be treated with strong acids to effect its rapid solution.

If the content of aluminum and iron oxides in the phosphate rock exceeds 3 or 4 per cent, the superphosphate that is made from it tends to be sticky and does not "cure out" as satisfactorily as that made from the better grade of rock. Phosphate rock of such quality is useful only in the raw and finely pulverized state or may be employed in the production of phosphoric acid by the volatilization process.

THE MANUFACTURE OF CONCENTRATED PHOSPHATES

As a means of economizing on freight and also for the economical utilization of low-grade phosphate rock, it has been found desirable to produce more concentrated phosphates. Three such materials are now being produced under the names of treble-superphosphate, ammonium phosphate, and calcium metaphosphate. Calcium metaphosphate is as yet only in the experimental stage of production. Its effects are similar to those produced by basic slag.

The treble-superphosphates are made by treating phosphate rock with an excess of sulfuric acid, washing out the resulting phosphoric acid, and using this for the acidulation of more phosphate rock. In this way the calcium sulfate, which ordinarily makes up approximately 50 per cent of the superphosphate, is eliminated. Part of the treble-superphosphates on the market at present have their origin in Montana, where by-product sulfuric acid is produced in large quantities at points located in close proximity to the phosphate deposits. Their content of available phosphoric acid is usually about 45 per cent.

Phosphoric acid is also made by mixing phosphate rock with finely divided silica and coke and heating the mixture in an electric furnace. From the resulting phosphorus, by oxidation and the addition of water, orthophosphoric acid is produced. This may be treated with ammonia to form ammonium phosphate, or it may be employed for the acidulation of phosphate rock with the resulting production of concentrated superphosphate.

Ammoniated superphosphate is now the most important of the combined nitrogen and phosphoric acid fertilizer materials. It is made by treating ordinary superphosphate with anhydrous ammonia, or with one of several ammonia-containing liquors. This product differs from ammonium phosphate in that it contains not only monoammonium phosphate, but monocalcium and dicalcium phosphates and ammonium and calcium sulfates as well. Analysis of such a material usually shows between 2 and 4 per cent nitrogen and between 16 and 18 per cent phosphoric acid. Ammoniated treble-superphosphates can also be produced.

TESTS OF THE QUALITY OF PHOSPHATES

Since the treatments with sulfuric and phosphoric acids are designed to change the ground phosphate rock to the monocalcium and dicalcium phosphates, it is necessary to have some test by which the quantities of phosphoric acid that are present in these forms can be determined. The method by which this is accomplished is that of washing a sample of superphosphate with water, which removes the monocalcium phosphate, and then digesting the washed residue with a neutral solution of ammonium citrate for 30 minutes at a temperature of 65° C. This dissolves the dicalcium phosphate. The undissolved part of the phosphate rock remains on the filter after the citrate-soluble portion has been washed through with water.

By water-soluble phosphoric acid is meant that which is present in the superphosphate in the monocalcium phosphate form. Any free phosphoric acid would also be soluble in water, but this is normally not permitted in superphosphate since, if present, it would destroy the bags. However, any such phosphoric acid would tend to react with some of the remaining phosphate rock and would thus combine with calcium to form either the monocalcium or dicalcium phosphate. "Reverted" phosphoric acid is that which is present in the dicalcium phosphate form. The term indicates a belief that it is produced as a result of the reaction of monocalcium phosphate with tricalcium phosphate, but it is doubtful whether this reaction takes place in the process. Available phosphoric acid includes both the water-soluble and the citrate-soluble phosphoric acid. By insoluble phosphoric acid is meant, primarily, the undissolved phosphate rock.

The availability test that is employed for basic slag is that of solubility in a 1 per cent citric acid solution. The choice of this solvent was the result of the investigations of chemists in German experiment stations in which supplemental pot and field studies were made of the value of basic slag in comparison with bone meal and superphosphate. No solubility tests are made on bone, its total content of phosphoric acid and its fineness of division being the only points that are considered. Steamed bone has been shown to be more effective than raw bone, the chief reason being that it can be more finely pulverized. When phosphate rock is used in the unacidulated state, only its content of total phosphoric acid is determined. This is often reported in terms of the percentage of total phosphorus. To calculate this in terms of phosphoric acid, it must be multiplied by the factor 2.3.

RELATIVE AVAILABILITIES OF PHOSPHORUS IN VARIOUS CARRIERS

While superphosphate constitutes the major portion of the phosphate fertilizers, there is opportunity for choice between this material and either bone meal or basic slag. All three of these products carry their phosphorus in more available forms than does phosphate rock. They vary in their effectiveness, depending upon the conditions that obtain. Bone meal is likely to become available more readily on acid soils than on those containing limestone. Since superphosphate contains water-soluble phosphates, it is particularly useful in effecting a precipitation of any aluminum that may be present in the soil. This effect may be localized, but may suffice to stimulate the growth of the plant to such a point that it can withstand concentrations of aluminum that would have been injurious at earlier stages in its growth. Basic slag has considerable capacity to neutralize acid soils and for that reason is often preferred on pastures or on alfalfa where lime may not have been added. Basic slag, by reason of its neutralizing effect, also serves to precipitate aluminum and is more economical for this purpose than is superphosphate.

Of the numerous comparisons that have been made of the relative effectiveness of the several carriers of phosphorus, the following is selected because the soil on which the test is being made is very deficient in available phosphoric acid, and the crops that are grown are quite responsive to phosphate fertilizers. Equal quantities of phosphoric acid are supplied in each case. The soil receives occasional treatments of lime, as required, and is given a basic treatment of nitrate of soda and muriate of potash, at a rate of 480 pounds of the former and 260 pounds of the latter, each five-year period.

TABLE 131

AVERAGE ACRE INCREASES FROM USE OF PHOSPHATES* (THORNE)

Carrier of Phosphorus	Corn, Bu.	Oats, Bu.	Wheat, Bu.	Clover, Cwt.	Timothy, Cwt.
Superphosphate	13.37	14.54	14.21	8.79	6.72
Steamed bone	8.59	11.23	11.38	8.73	4.03
Basic slag	11.32	11.26	13.58	6.89	6.69

* Thirty-year averages on land which receives basic treatments of lime, nitrate of soda, and muriate of potash. Each phosphate is applied in quantities to supply 45 pounds of phosphoric acid an acre every 5 years.

These and other experimental tests favor the use of superphosphate, assuming that a unit of phosphoric acid costs the same in all three carriers. It is well to remember that the comparison is on the basis of equal phosphoric acid contents as measured by the use of neutral ammonium citrate solution; a strong acid solution; and 1 per cent citric acid solution for superphosphate, bone meal, and basic slag, respectively. All three of these phosphates have been found to be highly useful on soils that are deficient in available phosphoric acid.

RELATIVE VALUES OF SUPERPHOSPHATE AND PHOSPHATE ROCK

In the early history of the use of phosphate rock, it was shown that this material would not give results comparable with those of bone meal unless it was treated with sulfuric acid to render the phosphoric acid more soluble. Sir John Lawes, of Rothamsted, first undertook the manufacture of superphosphate on a commercial scale in 1843. Since that time it has gradually grown in favor until now it constitutes the major portion of the phosphate that is used for fertilizer purposes. Later, the machinery for pulverizing phosphate rock was so improved that it was believed possible that the finely ground product might be equally as effective as the superphosphate. The most prominent advocate of ground phosphate rock was the late Cyril G. Hopkins, of the University of Illinois, whose arguments in favor of its use were given wide publicity.

An examination of the data that are available on comparative tests of superphosphate and phosphate rock shows some very interesting facts. One of these is that, if the soil is strongly acid, the phosphate rock is somewhat more effective, relatively, than when the reaction of the soil is approximately neutral. This is indicated in Table 132,

TABLE 132

ACRE YIELDS WITH USE OF SUPERPHOSPHATE AND PHOSPHATE ROCK* (WIANCKO)

Phosphate	Corn		Wheat		Clover	
	Unlimed, Bu.	Limed, Bu.	Unlimed, Bu.	Limed, Bu.	Unlimed, Cwt.	Limed, Cwt.
Superphosphate	27.9	26.5	11.5	14.3	13.8	19.5
Rock phosphate	31.8	28.0	16.3	12.1	19.5	19.9
S.P. complete fertilizer	37.8	38.9	14.5	16.5	19.5	22.6
R.P. complete fertilizer	39.0	37.8	18.5	14.6	23.4	24.0
S.P. and manure	44.6	45.7	19.0	18.2	22.8	23.7
R.P. and manure	44.5	44.5	21.0	18.4	27.4	24.9
No fertilizer	21.9	25.3	4.8	7.6	9.0	12.5

* Last 8 years of a 22-year period. All the fertilizer and manure are applied to the corn crop. Enough superphosphate is used to supply 48 pounds of available P_2O_5 an acre. The phosphate rock supplies 192 pounds of total phosphoric acid an acre.

showing the last 8 of 22 years' comparative tests of the two materials on the heavy silt-loam soils of southern Indiana. The rate of application of the superphosphate was half that of the phosphate rock, the superphosphate originally costing twice as much per ton as the phosphate rock. The superphosphate supplies 48 pounds of available phosphoric acid to an acre every third year for the corn crop, while the phosphate rock supplies four times as much total phosphoric acid.

Probably the most significant comparative test of these two phosphates is that which is being carried on under the direction of workers at the Ohio Experiment Station, the data for which are given in Table 133. In this test, comparisons are made of 8-ton applications

TABLE 133

ACRE INCREASES FROM USE OF SUPERPHOSPHATE AND PHOSPHATE ROCK* (THORNE)

Fertilizer Treatments	Corn, Bu.	Wheat, Bu.	Clover, Cwt.
Superphosphate and manure	34.33	15.10	21.96
Phosphate rock and manure	30.14	12.87	17.75
Gypsum and manure	27.89	10.55	10.80
Manure alone	23.87	9.97	9.97
Unmanured yields	36.87	14.18	29.37

* Twenty-six-year averages from use every third year, of 8 tons of manure, each ton re-enforced with 40 pounds of superphosphate or phosphate rock.

of manure on corn in rotation with wheat and clover. The manure on one set of plots is re-enforced with superphosphate applied at the rate of 40 pounds a ton, while that on another series of plots receives the same amount of phosphate rock. Several important facts should be noted before studying these data: the soil is limed from time to time as the need becomes apparent; the phosphate rock supplies twice as much phosphoric acid as the superphosphate; none of the three crops is especially noteworthy as being able to secure phosphorus from phosphate rock; and superphosphate contains about 50 per cent of calcium sulfate, which is apparently of some value when applied separately to manure.

In spite of the fact that the phosphate rock supplies twice as much phosphoric acid as does the superphosphate, there is no evidence that this extra phosphoric acid has any cumulative effects. The longer the experiment is continued, the more the yields on the phosphate rock plots fall behind those on the plots receiving superphosphate.

VALUE OF THE CALCIUM SULFATE IN SUPERPHOSPHATE

Evidence is presented in Table 133 which indicates that a part of the value of superphosphate, at least when used with manure, lies in the calcium sulfate which makes up about 50 per cent of its weight. A combination of phosphate rock and calcium sulfate might possibly be as effective as is superphosphate. It is known that calcium sulfate aids in retaining the ammonia of manure. It has also been demonstrated that sulfur is an essential element in plants and that in certain parts of America the soils are deficient in this element. Of the data that are available on this subject, those that are reported from the Washington and Oregon Experiment Stations are of greatest interest. They show the importance of sulfur applications, particularly on crops like alfalfa which contains practically the same amount of sulfur as of phosphorus. The data shown in Table 134 are typical of the results that have been secured in these tests.

TABLE 134

ACRE YIELDS OF ALFALFA WITH AND WITHOUT SULFUR (REIMER)

Treatment	Rate, Lb.	Alfalfa,* Cwt.
None	0	19.7
Sulfur	300	136.6
Gypsum	600	164.1
Monocalcium phosphate†	320	28.6
Superphosphate	820	164.8
Muriate of potash†	530	31.2
Sulfate of potash	550	152.8
Nitrate of soda†	560	31.8
Sulfate of ammonia	420	146.8

* Total crop produced in three-year period. The soil and subsoil contained 0.20 and .017 per cent of sulfur, respectively.

† These materials contain little or no sulfur.

In the earlier analyses of plants, a considerable part of the sulfur was lost by volatilization in the process of incineration. This fact not being known, the importance of the element sulfur in plant and animal economy was not appreciated. Later it was shown that the content of sulfur in plants and soils is quite similar to that of phosphorus and the problem of economy of the two elements is somewhat similar. However, there are several points in which they differ. Sulfur is not required in such large amounts by animals. There is a sulfur cycle by way of the atmosphere, which renews the supply in the soil. In industrial sections, this return to the soil in the rainwater is believed to be sufficient to meet the needs of crops. Analyses of rainfall have shown varying amounts of sulfur, depending upon the proximity of cities and industrial plants in which large amounts of coal are consumed. Another source of large amounts of sulfur is the smelters for roasting sulfide ores. That the sulfur dioxide thus produced is widely distributed by the atmosphere is indicated by the fact that at Urbana, Ill., which is located near the center of the Corn Belt and at some distance from smelters and large cities, the sulfur content of the rainfall was found to exceed 40 pounds to an acre, each year. While the loss of sulfur in livestock and its products is less than that of phosphorus, the drainage losses of the sulfur are much greater than those of phosphorus.

The beneficial effects of landplaster, particularly on somewhat unproductive soils, have long been known. It is said that Benjamin Franklin wrote, with landplaster, "This land has been plastered," on a hillside near Philadelphia, and that the words could be read by the passersby because of the remarkable increase in the growth of grass. At one time landplaster was a very popular fertilizer, but later its use fell into disrepute. The explanation is that the consumption of coal increased enormously; the smelting industry assumed large proportions; and the use of superphosphate, with its content of calcium sulfate, made the additional application of landplaster unnecessary.

Landplaster serves a number of important purposes in agricultural practice. It is useful as a preservative for manure. Peanut growers use it as a topdressing to stimulate the growth of that crop. In regions that are far removed from industrial centers, it is a very necessary fertilizer, especially on crops such as the crucifers, alfalfa, and onions, which require large amounts of sulfur. In all these ways superphosphate is equally useful and has the added advantage that it supplies phosphorus, which is also essential as a fertilizer. If sulfur is needed, such materials as treble-superphosphate and ammonium phosphate will not be adequate since they contain little or none of this element. However, gypsum could be mixed with these materials in such amounts as might be necessary to satisfy the sulfur requirements of the crops. If nitrogen or potassium fertilizers were required, these could be supplied in the form of sulfates.

CAPACITIES OF PLANTS TO FEED ON PHOSPHATE ROCK

There is evidence to support the belief that those plants that require considerable amounts of calcium may be able to utilize the phosphorus of phosphate rock more readily than can plants that are low in their content of this element. The explanation is found in the fact that phosphate rock can be used to best advantage on somewhat acid soils. In either case, if the calcium acid carbonate that is produced as a result of the solvent action of carbonated water on phosphate rock is removed from the field of action by the plant or by the exchange complex, more phosphoric acid can move into solution than if this dissolved calcium accumulated at the point of solution.

In testing this assumption, it was found that there was no very good correlation between the calcium content of the tops of plants and their capacities to utilize the phosphorus of phosphate rock. The discrepancies were explained on the basis of differences in the character of the root systems of plants. Those having an extensive development of

TABLE 135

Relative Capacities of Plants To Feed on Phosphate Rock (Bauer)

With Low Feeding Power		With High Feeding Power	
Plant	Relative Growth*	Plant	Relative Growth*
Red clover	33	Rape	54
Wheat	34	Alfalfa	62
Oats	41	Rye	66
Corn	41	Buckwheat	72
Timothy	45	Red top	72
Soybeans	47	Sweet clover	83

* By comparison with normal growth produced as a result of the use of superphosphate.

fibrous roots seem to be able to secure a larger amount of the phosphorus from phosphate rock, probably because these roots come into contact with more of it in the soil as it goes into solution. Whatever the explanation, the fact remains that plants vary in their response to the use of phosphate rock. The choice between superphosphate and phosphate rock will be determined in part by the crops to be grown. If, for example, sweet clover is to be used as a green-manure crop, it would seem probable that phosphate rock could be used to advantage.

A BIOLOGICAL PROCESS FOR MAKING SUPERPHOSPHATE

A study of the activities of organisms that oxidize sulfur led Lipman to suggest the use of elemental sulfur on phosphate rock as a means of producing superphosphate. Extended investigation showed that this was a feasible process. The plan followed was that of mixing 4 parts of phosphate rock with 1 of sulfur and inoculating the mixture with the sulfur-oxidizing bacteria. When the inoculated mixture is kept under suitable conditions of temperature and moisture, sulfuric acid is produced; this reacts with the phosphate rock to form superphosphate that is much the same as the commercial product. It is believed that this process could be used on a commercial scale, but so far little has been done with it because most fertilizer factories are using the sulfuric acid process and many of them have their own acid plants.

ADSORPTIVE CAPACITIES OF SOILS FOR PHOSPHORIC ACID

Most soils have marked capacity to fix soluble phosphates and render them insoluble in water. Part of the fixed phosphate is adsorbed by the colloidal complex. The remainder is precipitated as insoluble phosphates of iron, aluminum, or calcium — the first two in strongly acid soils, and the last in near-neutral or alkaline soils. It would seem, on this basis, that little is gained by acidulating phosphate rock before applying it to the soil. However, one important effect of the acidulation is to separate the calcium fluoride from the phosphate molecule. If care is taken to apply the resulting superphosphate in bands, that in the center of these bands may escape fixation. Furthermore, any of the phosphate which is precipitated by iron, aluminum, or calcium goes into solution more readily than that in the original phosphate rock no matter how finely the rock may have been pulverized.

Any excess of phosphate that is applied to the soil accumulates in it. The users of phosphate rock adopt the policy of doubling the phosphate content of their soils and then try to maintain the phosphate supply at this level. This does not necessarily guarantee that adequate surface areas are exposed to the solvent action of the soil water. Neither does it take into consideration the fact that apparently one of the important functions of superphosphate is that of effecting the temporary removal of soluble aluminum from solution.

SOME SPECIAL USES OF PHOSPHATE FERTILIZERS

It has long been known that certain crops respond very markedly to applications of phosphates. The classic example of such response is the turnip. This plant has been used as an indicator of phosphorus deficiencies of soils since its rate of growth and phosphorus content are closely correlated with the phosphorus content of the soil. Clovers are also very responsive to applications of phosphates. For this reason, superphosphate and basic slag are very effective on pastures as a means of stimulating the growth of white clover through the agency of whose nodule bacteria the necessary nitrogen is accumulated from the air. Nitrogen fixation by azotobacter is also very much increased by the addition of phosphates to the medium in which they are growing.

A deficiency of phosphoric acid in the soil results in a failure of wheat plants to produce plump kernels of grain. A deficiency of some other element might cause the same result, but much of the increase in yield of wheat and other cereals can be accounted for in the very small percentage of shriveled kernels that are produced when plenty of available phosphorus is present in the soil.

Maturity of the crop is hastened by the use of liberal amounts of phosphates in contrast to the effect produced by heavy applications of either nitrogen or potash fertilizers, particularly the former. This may be of little importance with the cereal crops, but is of considerable

TABLE 136

EFFECT OF SUPERPHOSPHATE ON MATURITY AND YIELD* OF TOMATOES (HEPLER)

Superphosphate Supplied per Acre	None	500 Lb.	1000 Lb.	1500 Lb.
Harvesting Dates:				
August 15	108	345	648	456
August 23	143	641	900	724
August 27	225	962	1,274	1,096
September 3	507	1,906	3,122	2,413
September 6	1,067	4,231	6,779	5,472
September 12	2,123	7,653	11,797	9,974
September 18	4,048	13,330	18,069	17,508
October 1	17,565	23,153	25,646	27,422

* For 1 year only, but similar results were obtained each year during the 5-year period covered by the test. All the plots received 20 tons of manure per acre in addition to the superphosphate. The data are cumulative and show the total crop that had been harvested at the date indicated.

FIG. 45. Before the application of lime and mineral fertilizers.

value in such crops as tomatoes which often command a very high price early in the season. This is well shown in Table 136, which gives the yields of tomatoes that had been produced at various dates as affected by the amount of superphosphate that had been applied. It is well to keep in mind, in this connection, that in dry seasons liberal applications of phosphates may not only hasten the ripening period but may also bring the plant to maturity before the rains occur, with a resulting decrease in yield.

PHOSPHATES AS PARTIAL SUBSTITUTES FOR NITROGEN FERTILIZERS

Within limits, phosphate fertilizers, together with potash salts and lime, can be substituted for nitrogen fertilizers. Their use stimulates the nitrogen-fixing bacteria, both the non-symbiotic and those associated with legumes, to greater activity. This fact is well illustrated in Figs. 45 and 46, which show the changes which took place in a worn-

FIG. 46. Two years after the application of lime and mineral fertilizers.

out pasture, following the application of mineral fertilizers and lime. The rank growth of white clover that developed on the treated area produced an effect on the grass which was quite similar to that resulting from an application of nitrogen fertilizer. Extra nitrogen can usually be used to advantage on pastures, but its value often lies primarily in stimulating early growth, and in lengthening the grazing season, assuming that clovers are abundantly contained in the sward.

The value of phosphate and potash fertilizers and of lime as agents to stimulate nitrogen fixation is even greater for annual or biennial legumes in crop rotations, since grass and weed competition for space can be largely eliminated and the legumes can be made to function more effectively. In the growing of perennial legumes like alfalfa, a difficult problem is presented in trying to supply adequate amounts of phosphate to meet the needs of these legumes for continuous growth. Excessive fixation occurs if heavy applications of phosphate are made in advance of seeding, and topdressing applications after the crop is started are usually not very effective. The only practical method of dealing with this problem is to plow up the legume from time to time and reseed.

RÉSUMÉ CONCERNING THE USE OF PHOSPHORUS FERTILIZERS

There is no atmospheric supply of phosphorus. The quantity in the soil is relatively small. In proportion as crops and livestock are sold from the farm, the element phosphorus is carried off with them. This loss must be compensated for by the use of phosphate fertilizers. Phosphorus is the predominating element in the fertilizers that are used on the grain crops. As a constituent of the fertilizers that are used on market-garden and other special crops, it is equally as important as nitrogen or potassium. Phosphate fertilizers are especially important in the production of roots, cereals, and clovers; they hasten the maturity of the crop; they are useful in precipitating aluminum in acid soils. The most important phosphate fertilizer is superphosphate. It meets the requirements under almost all conditions as well as, or better than, any other carrier of phosphoric acid. In recent years, however, the more concentrated double- and treble-superphosphates, ammonium phosphates, and ammoniated superphosphates have come on the market in large tonnages. They have the advantage of lower freight costs per unit of available phosphoric acid. The supply of phosphate rock in sight in the United States is very large and is sufficient to meet our needs for several thousand years.

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CHAPTER XXIII

POTASH FERTILIZERS

Soils that contain relatively high percentages of silt and clay are usually well supplied with potassium. The average soil carries about 30,000 pounds of the element in the plowed acre. In contrast with nitrogen and phosphorus, the potassium content of subsoils is usually higher than is that of surface soils. Considered from the point of view of the entire depth of soil which the roots of crops penetrate, the quantity of potassium is such that there is little danger of its exhaustion by crop removal for many years to come. On the other hand, it has been shown that most soils which have been farmed for a quarter of a century or more will produce somewhat larger yields of crops if some soluble potassium salt is applied to them. Most of the potassium that is contained in the soil is present in a form or condition in which it cannot readily be extracted with water, or displaced with salt solutions. Much of it cannot be brought even into solution by digesting the soil with strong acids.

POTASSIUM ECONOMY IN GENERAL FARMING

A large part of the potassium of plants is contained in the stalks, only a relatively small quantity being stored in the grain. Any system of cropping that returns the leaves and stems to the soil need not be seriously exhaustive of the supply of this element. In grain farming, the stalks of corn and the straw of wheat and oats are not usually removed from the farm. Frequently the clover crop, if grown, is plowed under. If these crop residues are evenly distributed over the field before being incorporated with the soil, it should be possible to maintain the content of available potassium in the soil at a point that would continue to meet the requirements of crops for many years. The most important losses which might then occur are those of the drainage water. Fortunately, potassium is an element for which most soils have marked adsorptive capacities, so that losses in this manner are not as serious as might be anticipated from the high solubilities of most of the salts of this element.

Unfortunately, farmers often fail to return the crop residues to the soil or to effect their proper redistribution. In the grain system of farming, it has been the common practice to burn the cornstalks and straw. The only soil element that is completely volatilized in this process is nitrogen. The mineral elements remain, for the most part, in the ashes. However, the stalks, straw, and other crop residues are usually burned in heaps and the ashes are distributed over relatively small areas instead of being evenly spread over the field. Evidence of the excessive concentration of potassium that occurs in these ash heaps is found in the fact that often no crop can be grown for several years on the place where a heap of brush or a straw stack has been burned. Later it will be found that this spot is very productive and that its crop-producing capacity continues for many years to be higher than that of most of the remainder of the field.

In the livestock system of farming, practically all the potassium can be returned to the soil in the manure since this element is retained only slightly by animals. The following table is of interest in this connection in that it shows the relatively high recovery of the potassium of the feed in the excrement of dairy cows as compared with that of phosphorus and nitrogen. These tests were run for intervals of only five days. If such a test could be run for an entire year, it seems probable that more than 90 per cent of the potassium could be accounted for in the urine, feces, and skin excretions.

TABLE 137

Percentage Recovery of Fertilizer Elements of Feeds in Manure (Wells)

Cow	Nitrogen	Phosphorus	Potassium
1	67	39	73
2	73	43	95
3	69	42	81
4	65	37	68

It is evident that potassium is recovered in larger percentages in the excrements than are the other fertilizer elements. The potassium problem in livestock farming would seem to be largely one of returning the manure to the field without loss. Such losses as must inevitably occur through leaching and drainage could conceivably be compensated for by making more of the potassium of the soil available. Once potassium has been used by plants, it should be possible to keep it in circulation indefinitely, although, in each cycle of return to the soil and plant, some would be lost. Green-manure crops, the second growth of clover, and the usual crop of weeds that grows each season should help in extracting the amount from the soil that is necessary to supply the deficit.

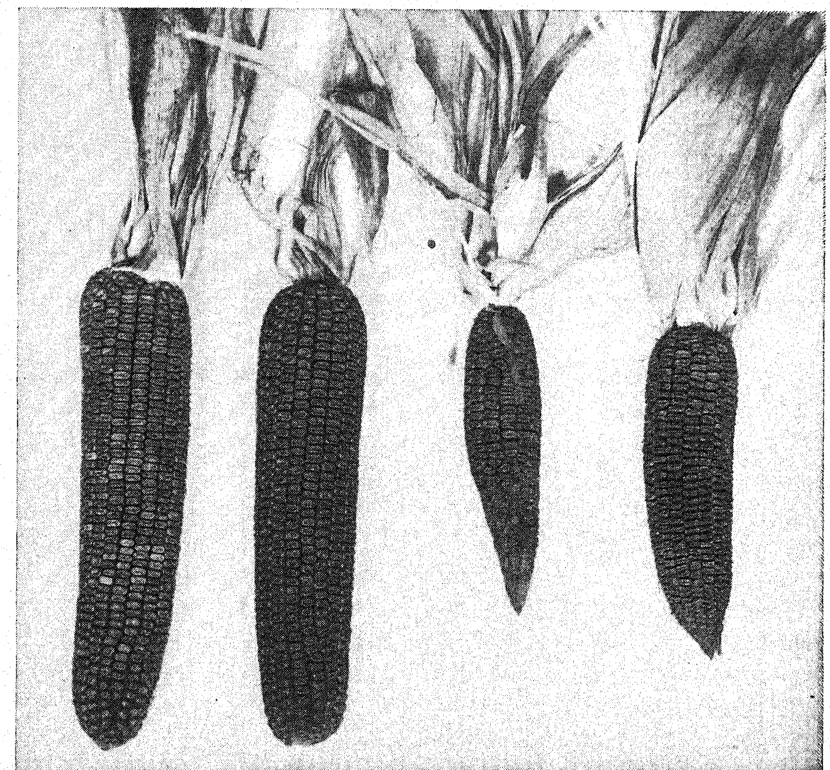
POTASSIUM ECONOMY IN INTENSIVE FARMING

In specialized crop farming, in vegetable gardening, and in truck farming, the opportunities for the profitable use of potassium fertilizers are especially good. Some of these crops, when sold, remove considerable amounts of potassium from the farm. A ton of tobacco leaves contains 25 to 40 pounds of potassium. Fifty pounds of potassium are sold with 300 bushels of potatoes, a yield that can reasonably be expected from an acre of good land. It happens that most of the truck and vegetable crops are grown on sand and muck soils that are relatively quite low in their potassium content. Many of these soils are also subject to heavy losses by leaching. An additional reason for the greater need of potassium fertilizers on market garden and truck crops is found in the fact that high acre yields are required for their profitable production. To produce these high yields it is necessary to maintain the soil nutrients at a concentration considerably higher than that normally existing in the soil after it has been subjected to the leaching action of rainwater. This materially increases the drainage losses of such elements as nitrogen and potassium.

If manure is available in abundance, the need for potassium fertilizers for market gardening and truck farming is very much reduced. As previously suggested, advantage may also be taken of green-manure crops as a means of releasing more potassium from the soil and of increasing the concentration of the element in the soil solution. Usually, however, in addition to such practices, liberal amounts of potassium fertilizers can be used to advantage on specialized crops. Even in general farming, in proportion as economizing in potassium has been neglected, as it seems advisable to sell crops or parts of crops which carry considerable amounts of potassium from the farm, as the soil is naturally deficient in this element, and as the price of farm crops advances or the cost of potash is lowered relatively, larger amounts of potassium fertilizers can be used to advantage.

SOURCES OF FERTILIZER POTASSIUM

In 1843, a deposit of salts consisting of a mixture of potassium, magnesium, sodium and calcium sulfates and chlorides was encountered at a depth of about 800 feet, in a boring made in the hope of finding common salt, near Stassfurt, Germany. Continuation of the boring showed that this deposit had a depth of more than a thousand feet, but that the salts were of little value for the purpose for which they were sought. At that time, potassium salts were not being used for fertilizer purposes. Later, when their value for soil-improvement purposes was discovered,



Purdue University.

(a) (b)

FIG. 47. When corn starves for potash, the leaves fire along the edges, and the ears are chaffy and of poor feeding value. (a) Potash. (b) No potash.

further investigation of these deposits was undertaken, with the result that they were found to underlie large areas of land at several different points in northern Germany and in Alsace-Lorraine.

Present estimates of the German deposits place them at over 12 billion cubic yards of potassium salts. Those of Alsace-Lorraine are estimated at over 200 million cubic yards. The deposits lie at varying depths and differ considerably in thickness. Ordinarily no salt is mined at a depth of more than 4000 feet by reason of the high temperatures that are encountered. About 150 mines were once being operated. In 1922, the total production of these mines amounted to over 15 million metric tons of crude salts.

The three most important of the crude natural salts are carnallite, kainit, and sylvinite or hardsalt. These contain approximately 9, 12 to 16, and 16 to 17 per cent of potash (K_2O), respectively. In addition, they carry large amounts of common salt and of the chlorides and sulfates of magnesium. The muriate[1] and sulfate of potash of commerce are made by refining the lower-grade salts. The muriate of potash is derived from carnallite, whereas the sulfate of potash is made by treating the muriate of potash with kieserite, which is largely magnesium sulfate.

Similar deposits of potash salts are found near Barcelona, Spain, and in the region of the Caspian Sea. Potash salts are also being obtained from the waters of the Dead Sea in Palestine. At various times, attention has been given to extracting potassium from easily decomposable silicates, such as alunite, leucite, glauconite (greensand), and feldspar. Considerable interest was once aroused in kelp as a source of this element. These latter sources of potash have commercial possibilities only in proportion as the fertilizer salts are yielded up as by-products in the manufacture of some other more costly chemical. Zeolitic materials that are useful in softening water are being made as primary products from greensand. With kelp, there are possibilities in the production of iodine and acetone.

TABLE 138

POTASH STATISTICS FOR THE UNITED STATES* (SHORT TONS OF K_2O)

Year	Production	Imports	Exports	Consumption
1929	61,000	325,000	10,000	376,000
1930	61,000	359,000	10,000	410,000
1931	63,000	214,000	19,000	259,000
1932	61,000	109,000	1,000	170,000
1933	143,000	214,000	16,000	340,000
1934	144,000	169,000	16,000	297,000
1935	192,000	243,000	45,000	390,000
1936	247,000	204,000	62,000	389,000
1937	284,000	351,000	61,000	574,000
1938	316,000	193,000	50,000	460,000

* These amounts are not necessarily consumed as of the years indicated, the carry-over varying from season to season.

Table 138 gives the statistics of potash production, of imports and exports, and of consumption for the years 1929 to 1938. It may be well to recall the fact that the percentages of potassium are reported as potash, which is the oxide of potassium. Thus 78.2 pounds of potassium (K) are the equivalent of 94.2 pounds of potash (K_2O).

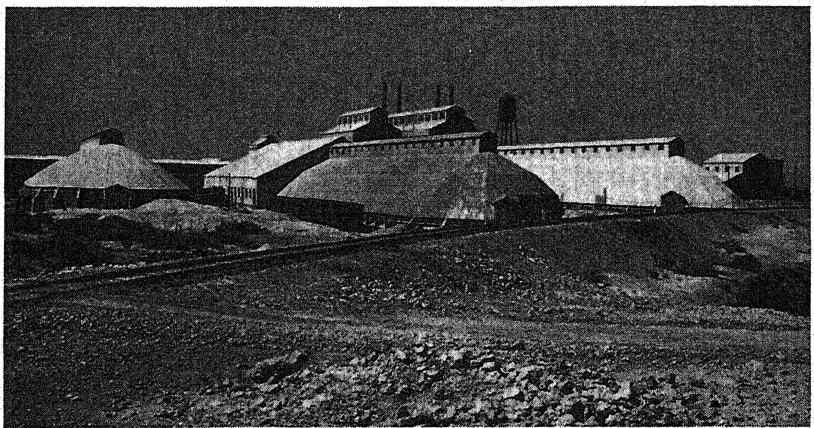
[1] Muriate of potash is the commercial name of the chloride.

THE AMERICAN POTASH INDUSTRY

For several years prior to the outbreak of the first World War, the United State had been importing, annually, approximately one million tons of potash salts, containing more than a quarter-million tons of actual potash (K_2O). This was largely of German origin. Most of this went into the fertilizer trade. With the beginning of war, importations ceased and potash salts became very high in price. An attempt was then made to develop an American potash industry. By 1918, 55,000 tons of potash were being produced in this country. Some of this was derived from kelp and some of it came from the salt brines of Searles Lake, California. The remainder had its origin as by-products of the cement, iron, beet sugar, alcohol, tobacco, hardwood, and wool industries. With the cessation of hostilities, Germany had lost part of her potash deposits to France. Competitive production and sale of potash salts soon resulted in prices so low as to hinder the further development of the American industry.

Nevertheless, production at Searles Lake, California, continued because these potash salts are co-products with borax and other sodium salts, for which there are extensive demands. Furthermore, the cost of the original plant had largely been written off during the period of World War prosperity.

Later, extensive potash deposits were found near Carlsbad, New Mexico. These are now being developed commercially. Even before the second World War began, these deposits were being worked on a large scale in successful competition with European producers. The



United States Potash Company

FIG. 48. Modern potash mining and refining plant at Carlsbad, New Mexico.

TABLE 139

TONS BY-PRODUCT POTASH* AVAILABLE IN AMERICAN INDUSTRIES (TURRENTINE)

Industry	At Present†	Potential
Blast-furnace	83,700	200,000
Cement	85,000	189,000
Borax	40,000	60,000
Alcohol	32,000	140,000
Sugar	7,000	16,000
Totals	247,700	605,000

* In terms of K_2O.

† Could be recovered at present, but most of it is lost.

output of American potash during 1938 amounted to over 600,000 tons of potassium salts, equivalent to 316,000 short tons of actual potash. The total potash consumption in the United States for that year was 460,000 tons.

It is quite clear that the United States now has an abundant supply of potash salts. Our potash refining industry is so well fortified with plant capacity and its methods of refining have been so modernized that European competition is no longer a disturbing factor. Foreign producers will no doubt continue to have an advantage in freight rates to shore points, but the great interior farming areas of the United States will obtain most of their potash from the domestic supplies.

CHARACTERISTICS OF VARIOUS CARRIERS OF POTASSIUM

The only test of availability of potash in fertilizers is solubility in water. Practically all potassium salts, with the exception of the complex aluminosilicates, are readily soluble. Most of the potassium of plant residues can also be extracted with water. The only characteristics that are ordinarily considered are the physical qualities of the various products, the nature of the associated ions in the several potassium salts, and the quantity and nature of the impurities that are present in the materials from which the potash is derived. The first is largely a matter of hygroscopicity. The second involves a choice among the chlorine, sulfate, nitrate, and carbonate ions. As to the last, consideration has been given so far largely to the effects of sodium chloride, magnesium sulfate and chloride, and borax, although other salts are known to be present in some of the lower-percentage materials from which a large part of the potash of fertilizers is derived.

PHYSICAL QUALITIES OF POTASH SALTS

Considerable difficulty has been experienced with carnallite by reason of its hygroscopic nature. On storage it tends to take on water and becomes difficult to handle. In proportion as magnesium chloride or common salt, particularly the former, is present in the salt mixture, the difficulty in this connection is increased. Of the imported potash salts, the sulfate of potash is usually much more finely divided and remains in better physical condition than the other salts. For that reason, it is to be preferred in home mixing, although usually potash in this form is somewhat more expensive than it is as the chloride or in the crude salt mixtures. Some of the American-mined muriate of potash contains over 60 per cent of potassium chloride and has very good physical qualities.

THE RELATIVE EFFECTIVENESS OF VARIOUS POTASH SALTS

Potassium nitrate and sulfate are, in some ways, to be preferred as sources of potash since the associated ions in these molecules are also useful to plants. They are not more generally used because of the extra cost involved in producing these salts for the market. Potassium carbonate has certain desirable qualities, when used on acid soils, for it has a neutralizing effect. On the other hand, the alkali carbonates are objectionable, if used in considerable amounts and on soils that are not acid, because of their deflocculating effect on the soil. The chlorides of potassium are most commonly employed and, in general, are more effective in increasing crop yields than are any of the other potash salts. On certain crops, however, objectionable effects have been noted from the use of chlorides, of which particular mention should be made of tobacco, sugar beets, and potatoes. With tobacco, excessive chlorine is found to impair the burning qualities of the product. In beets and potatoes, too much chlorine seems to depress the sugar- and starch-formation processes. The evidence does not indicate that such effects will be secured from the use of ordinary amounts of muriate of potash; but they are likely to occur when kainit is employed in considerable amounts, unless it is added to the soil some months in advance of the sowing or planting of the above-mentioned crops. In this event, much larger amounts of chlorine are added since kainit not only contains a smaller percentage of potash but also carries large amounts of additional chlorides in the form of sodium and magnesium salts.

It is not feasible to attempt to present any large array of experimental data on this subject. The following comparison of three carriers of potash is of interest and indicates, as does most of the experimental work on the subject, that, if there is any preference as to yield, it lies with the muriate.

TABLE 140

COMPARATIVE ACRE INCREASES* WITH VARIOUS POTASH SALTS (THORNE)

Carrier of Potash	Tobacco, Cwt.	Wheat, Bu.	Clover, Cwt.
Nitrate of potash†	2.17	1.18	1.30
Sulfate of potash	1.86	1.00	0.79
Muriate of potash	1.86	1.40	2.46
No potash yield	10.09	25.19	36.88

* Twenty years' average acre increases from the use of 90 pounds of potash (K_2O) an acre applied to the tobacco crop. All the land received a basic treatment of 480 pounds of superphosphate (16 per cent) and 240 pounds of nitrate of soda.

† Here the nitrogen was in the form of nitrate of potash.

EFFECT OF OTHER SALTS IN POTASH FERTILIZERS

The three common impurities in German potash salts are magnesium sulfate, magnesium chloride, and sodium chloride. No particular objection has been raised to the presence of magnesium although it is evident that, if for any reason the soil contains more magnesium than calcium in solution, the addition of soluble salts of magnesium would probably result in some injury or lowering of the yields. This is more likely to occur in acid soils than in those that contain adequate amounts of lime. On the other hand, there are certain conditions in which the presence of magnesium salts in the mixture is desirable. The best example of this is found in connection with a type of chlorosis which has been noted in certain cases in growing tobacco. This diseased condition, known as *sand drown*, is overcome by the use of dolomitic limestone or of potash fertilizers carrying magnesium salts.

During the first World War, domestic potash from western salt lakes which carried considérable amounts of borax was put on the market. Some very injurious effects were noted, particularly in the potato districts of New England and in the southern Cotton Belt. When it was discovered that borax was responsible for the injury, the processes of refinement of the salts were so improved that most of this compound was eliminated from the fertilizer. Small quantities are not objectionable and, in fact, are often required for satisfactory crop growth on soils that are deficient in boron.

ASHES AS SOURCES OF POTASH

Wood ashes have long been used for soil-improvement purposes. They contain considerable amounts of potash, and in addition carry relatively large amounts of lime. Both the potash and lime are changed to the carbonate form on exposure. If subjected to leaching, the potassium carbonate is lost. This constitutes the "lye" that was formerly used in the manufacture of soft soap. Ashes from other plant residues also contain potash and other inorganic elements. Those from coal are of least value, since apparently most of the potassium was leached from the plant materials before the coal-forming process became effective. Table 141 shows the partial analyses of the ashes of a number of refuse materials.

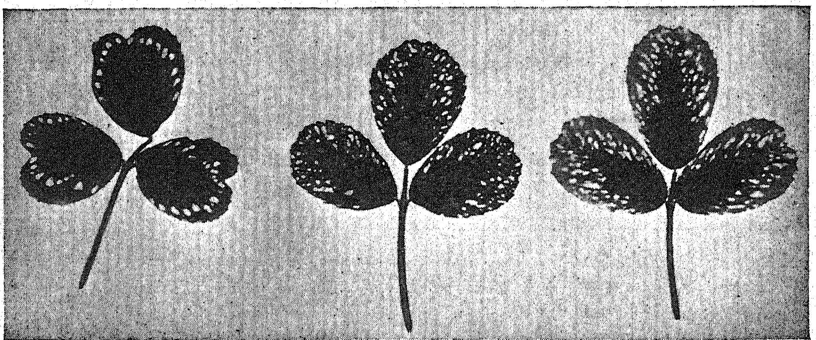
TABLE 141

PERCENTAGE COMPOSITION OF ASHES OF REFUSE MATERIALS (JENKINS)

Material	K_2O	P_2O_5	CaO
Canada hardwood	3–5	1–1.5	25–30
Household wood	3–8	3	34
Citrus fruit skins	25–30	3–6	.....
Banana skins	42	3	.....
Corn cobs	17–21	3–4	.....
Coal*	0.1–0.4	0.1–0.4	.....

* Analyses from other sources.

A supplemental benefit is derived from plant ashes by reason of the fact that the potash is present as the carbonate which has a neutralizing value on acid soils. Ashes also contain calcium oxide which gradually changes to the carbonate form. Unleached hardwood ashes have a neutralizing value equivalent to over half their weight of ground limestone. The good effects on clover that are commonly noted as a result of the use of ashes must be credited in part to their value for correcting soil acidity.



Emil Truog, Wisconsin Agr. Exp. Sta.

FIG. 49. Effect of potash deficiency on the leaves of alfalfa.

SUBSTITUTION OF SODIUM FOR POTASSIUM IN FERTILIZERS

A considerable number of field tests of common salt have been made at various experiment stations in this country and in Europe. The effects of the use of salt are somewhat conflicting; but, in general, it has been shown that when potassium is deficient, sodium is effective in increasing crop yields. The evidence indicates that it serves as only a partial substitute for potassium in one or more of the several functions which the latter element performs either in the soil or in the plant. The most complete data on this subject are reported from the Rhode Island Experiment Station. From these investigations, it seems safe to conclude that substantial increases can be expected where there is a partial deficiency of potassium from the use of common salt as a fertilizer on turnips, beets, mangels, radishes, and rutabagas.

An interesting test of salt as a fertilizer is recorded in the following table in which are shown the yields of sweet potatoes, when grown on Norfolk sandy loam soil, as determined by the quantity of salt that was applied. The usual treatment of 1000 pounds of 5–8–7 fertilizer an acre was supplemented with various amounts of salt applied as a topdressing as soon as the plants were well rooted and worked into the soil by subsequent cultivations.

TABLE 142

AVERAGE ACRE YIELDS* OF SWEET POTATOES WITH AND WITHOUT SALT (JOHNSON)

Fertilizer Treatment	Early Harvest	Late Harvest	Relative
Complete fertilizer, 5–8–7	232	267	100
Same + 500 pounds salt	270	294	113
Same + 1000 pounds salt	300	338	128
Same + 1500 pounds salt	286	304	119
Same + 2000 pounds slat	305	333	128

* Bushels per acre as an average of three seasons.

THE EXCHANGE COMPLEX IN RELATION TO POTASSIUM

Plants obtain their potassium from the exchange complex of the soil, the seat of which is the colloidal matter. The proportions of the several cations which are attached to the complex vary, depending upon the past history of the soil. The exchange capacity is usually given in milliequivalents, and normally lies between 2 and 20 milliequivalents per 100 grams of soil. Assuming the latter figure, the exchange complex of 2 million pounds of soil would have an absorbing capacity equivalent to 400 pounds of hydrogen. For optimum conditions for plant growth, probably 60 per cent of the exchange capacity should be satisfied by calcium and 10 per cent each by potassium and magnesium, the remaining 20 per cent being hydrogen. On this basis, one acre of soil to plow depth would contain 4800 pounds of exchange calcium, 1566 pounds of exchange potassium, and 487 pounds of exchange magnesium. This represents the available supply of these nutrient ions which would be at the disposal of the roots of plants.

Of interest in this connection are the following data showing the relative quantities of the several basic ions that were extracted from colloidal fractions of soils by treating them with a normal solution of ammonium chloride.

TABLE 143

PERCENTAGES* OF REPLACEABLE BASES IN SOIL COLLOIDS (MATTSON)

Basic Oxides	Sharkey Clay	Norfolk Sandy Loam
MnO	0.016	0.002
CaO	1.330	0.150
MgO	0.360	0.040
K_2O	0.130	0.070
Na_2O	0.030	0.020

* Percentages of dry weight.

By reason of the small content of replaceable basic ions in the Norfolk sand, the addition of considerable amounts of any salt such as sodium chloride would probably result in the liberation of relatively more potassium than would be the case with the Sharkey clay, which has a high content of replaceable calcium. The effectiveness of liming materials, of calcium sulfate, of common salt, and of the various fertilizer compounds is determined not only by their specific effects on plants but also by their indirect effects through alteration of the equilibria in the soil and resultant changes in the total concentration and in the ratios of the various ions in the soil solution. A soil whose exchange complex is saturated with basic ions in suitable ratios has lasting qualities far beyond that of one which has been subjected to leaching for centuries, and in which hydrogen ions have been substituted in large part for the basic ions. Land reclaimed from the sea, such as that of a large part of the Netherlands and that of the downs of southern England, is noted for the relative permanency of its productivity.

SOME SPECIAL NEEDS FOR POTASH FERTILIZERS

There are soils in which, even with good management, the lack of available potassium is likely to be a limiting factor in crop production early in their agricultural history unless this element is supplied in manure or in some commercial form. The most outstanding examples of such soils are found in mucks and sands and in soils containing high

TABLE 144

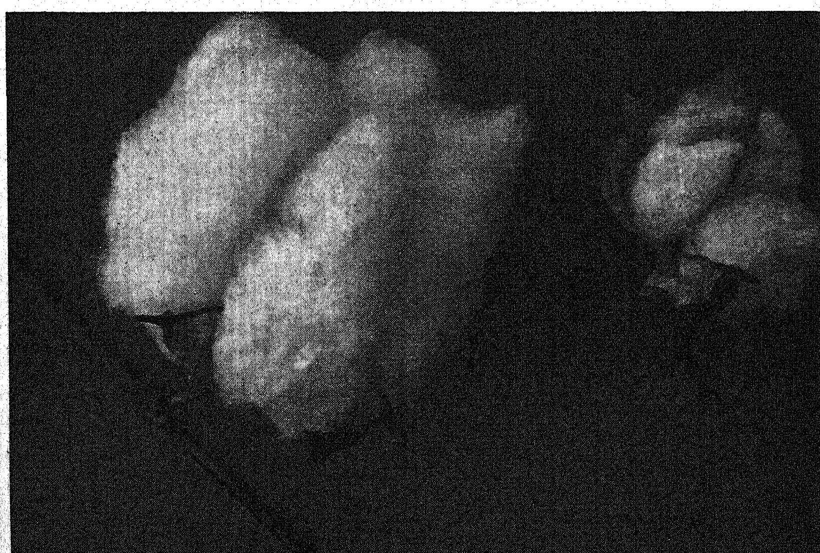
EFFECT OF POTASH SALTS ON ACRE YIELDS* OF ONIONS ON MUCK (CONNER)

County	No Fertilizer, Yield	N and P,† Increase	N, P, and K,† Increase	Effect of K, Increase
Benton	606	75	113	38
Kosciusko	353	41	66	15
Whitley	307	20	130	110
Jasper	423	12	202	190
Noble	394	47	89	42
Average	404	49	130	81

* Yields in bushels per acre.

† One thousand pounds of fertilizer per acre. N, P, and K indicate fertilizers carrying nitrogen, phosphate, and potash, respectively. The complete fertilizer contained 10 per cent potash.

percentages of carbonate of lime. On such soils the response of crops to the use of soluble salts of potassium is often quite remarkable. Table 144 shows the results of some experimental tests with potash



(a) (b)

FIG. 50. Effect of potash in filling out cotton bolls. (a) Plenty of potash. (b) Inadequate potash.

salts on some unproductive muck soils of northern Indiana. Table 145 gives the data from similar tests of potash salts on poor, sandy soils of Florida.

TABLE 145

EFFECT OF POTASH SALTS ON ACRE YIELDS* OF POTATOES ON SAND (FLOYD)

Year	N and P†	N, P, and K	Gain for K
First	34	69	35
Second	75	119	43
Third	100	146	46
Average	70	111	41

* Yields in bushels per acre.

† One thousand pounds of fertilizer per acre. The potash content of the complete fertilizer was 5 per cent.

RÉSUMÉ CONCERNING THE USE OF POTASH FERTILIZERS

The quantity of potassium in the average soil is quite large. Subsoils usually contain even higher percentages of potassium than do surface soils. Plant residues and animal manures contain relatively large amounts of this element in highly soluble forms. The total loss of potassium from the sale of products from a livestock or grain farm is not large. The losses of potassium by leaching are not as serious as would be expected from the known solubilities of most potassium salts since the soil has a marked adsorptive capacity for this element. It is possible to grow satisfactory yields of crops for many years on soils that are fairly well supplied with potassium without the purchase of any potassium in the form of fertilizers.

Notwithstanding these facts, it is found that potassium fertilizers are usually effective in increasing crop yields in humid climates on most soils that have been under cultivation for some years. Not all the manure is returned to the field. Crops other than grain are sold from the farm. Some losses do occur in the drainage water. In time a deficiency of this element usually occurs and then fertilizers carrying it are essential for satisfactory yields.

Certain soils, of which sands and mucks are notable examples, contain only relatively small amounts of potassium and are subject to serious losses by leaching. Such soils respond to the use of potash fertilizers early in their agricultural history. Certain crops, of which tobacco, potatoes, and onions may be cited as examples, respond to the use of potash fertilizers with marked increases in yield. In intensive systems of farming, complete fertilizers carrying potash as well as ammonia and phosphoric acid are to be preferred.

There is little choice among the various carriers of potassium except when used in large amounts on tobacco, and then the chlorides injure the quality. Similar objections have been raised to the use of chlorides for sugar beets and potatoes, but the evidence for these crops is less conclusive. Usually the muriate of potash produces somewhat higher yields than does any other salt of potassium, and for that reason, together with the fact that it is the cheapest form in which potash can be purchased, this salt or one of the crude salts from which it is derived is largely used in fertilizer mixtures. Common salt, liming materials, and landplaster may be of use under certain conditions in liberating potassium from the soil.

While most of the potash used in America formerly came from France and Germany, there is no longer any need to import this fertilizer constituent. In addition to the amounts that are produced as by-products in the industries, there are large quantities available from salt lakes in the western part of the United States, and extensive deposits in New Mexico are now being mined.

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CHAPTER XXIV

MIXED FERTILIZERS

The carriers of nitrogen, phosphoric acid, and potash can be purchased and used separately or they can be secured in the form of mixed fertilizers and applied all together. In general, the European farmer buys the ingredients and mixes his own fertilizer or applies the materials separately, depending upon the nature of the crop; on the other hand, the American farmer prefers to buy them already mixed unless he may have some special need for one or another of them to be used by itself. While a certain amount of mixing is done on the farm, the major portion of it is performed in fertilizer factories by manufacturers who are prepared to do it on a larger scale and in many ways better and more economically than it can be done by the farmer. The chief difficulty with factory mixing lies in the possibility of introducing into the mixture materials of doubtful quality. This is particularly so with the ammoniates, of which considerable quantities are to be had in the form of very low-grade materials.

THE FUNCTION OF THE CONTROL CHEMIST

Early in the history of the fertilizer industry it was recognized that it was necessary to have some means of determining whether or not fertilizers contained the ingredients that were claimed to be present and in such forms as would be available for crop use. As time went on, each of the various states employed a chemist to take charge of the analytical phase of this control problem as a means of protecting both the consumer and the honest fertilizer manufacturer against the manufacturer's unscrupulous competitors. As a result of many years of experience with this problem, the several control chemists, through their organization known as the Association of Official Agricultural Chemists, have adopted and published what are termed official methods for testing fertilizers. These are constantly undergoing revision not only because of the many improvements that are being made in the methods and in the details of their manipulation but also because new fertilizer materials are being used which require different analytical procedures to determine their quality.

Tests to determine the quality and percentage content of the phosphoric acid and potash in fertilizers are fairly satisfactory. There is somewhat more uncertainty about the tests of the quality of organic ammoniates. As a rule, however, the intelligent buyer is protected by the inspection service of each state through the report of the control chemist which shows the claims of the manufacturer in comparison with his findings. In general, the opportunity for the use of nitrogen materials of low availability is less in high-analysis fertilizers since these low-grade materials usually contain the fertilizer elements in such small percentages that high-analysis mixtures cannot be made from them. Unfortunately, in moving from what are now considered to be high-analysis fertilizers to others which can be produced and which are three or four times as concentrated, opportunity is again presented to the manufacturer to incorporate in the mixture such ammoniates as garbage tankage and peat, which are very good conditioners but, if unacidulated, may be of very little use as sources of nitrogen for plants.

THE MEANING OF CERTAIN FERTILIZER TERMS

Certain of the terms that are used in the fertilizer factory have found their way into the language of the fertilizer salesman and into the ordinary discussions of fertilizers. An examination of the statement of analysis that is guaranteed by the manufacturers is of interest in this connection.

TABLE 146

EXAMPLE OF STATEMENT OF ANALYSIS ON FERTILIZER BAG

	Per Cent
Total nitrogen*	6.00
Water-soluble phosphoric acid	6.00
Available phosphoric acid	8.00
Insoluble phosphoric acid	0.50
Total phosphoric acid	8.50
Available potash	6.00

* Most southern states require the manufacturer to state the source of any organic nitrogen that may be contained in the mixture.

The analysis indicates that this is what is termed a complete fertilizer, in that it contains carriers of nitrogen, phosphoric acid, and potash. It is said to be a 6–8–6 fertilizer, by which is meant that it contains such an amount of total nitrogen as would be equivalent to 6 per cent of nitrogen (N); an amount of "available" phosphorus equivalent to 8 per cent of phosphoric acid (P_2O_5); and an amount of "available" potassium equivalent to 6 per cent of potash (K_2O). Ordinarily very little is said concerning the sources of the various materials. Usually the phosphoric acid in complete fertilizers is derived from superphosphate or treble-superphosphate; the potash has its origin largely in the various water-soluble salts of potassium; and the nitrogen is derived mostly from inorganic salts, with sufficient amounts of organic materials to give condition to the mixture. It is in connection with the carriers of organic nitrogen that particular attention needs to be directed to the report of the control chemist.

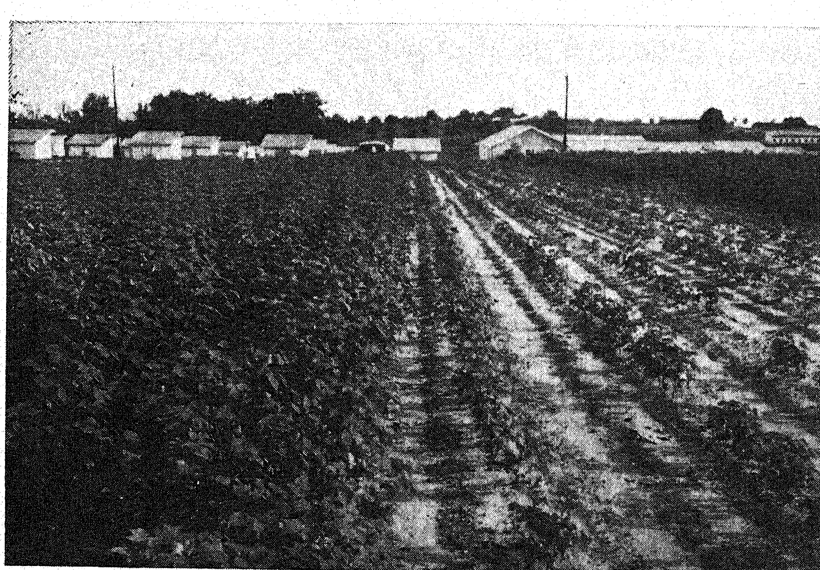
WET-MIXED FERTILIZERS

One of the arguments of fertilizer manufacturers in favor of factory mixing of fertilizers is that by this means an outlet is provided for all kinds of waste products of plant and animal origin which have little or no value for any other purpose. In the wet-mixing process these organic materials are mixed with the phosphate rock, and the entire mass is treated with sulfuric acid. After being processed in a silo, allowed to cure, taken out, and pulverized, the resulting material contains its nitrogen as well as phosphorus in more available forms. These base goods are then mixed with the required amounts of other materials to produce the ordinary complete fertilizers. The work of Hartwell and Pember, previously referred to, indicates that this process is effective in making the nitrogen of garbage tankage and similar materials much more available.

Many fertilizer factories are simply dry-mixing plants and, therefore, the organic materials that are used are not processed. This will be indicated in the report of the control chemists in those states in which such tests of the quality of nitrogen in mixed fertilizers are made. However, the fertilizer industry is becoming more of a chemical and less of a scavenger industry each year. An ever-enlarging percentage of the ingredients in these mixtures are inorganic compounds carrying the fertilizer elements in highly available forms. On the whole, the fertilizer manufacturers are rendering a valuable service to the farmer in taking over the entire problem of assembling and compounding the several fertilizer ingredients into mixtures of good mechanical condition for meeting the requirements of the crops to be grown.

HOME-MIXED FERTILIZERS

In the event that the mixing charge is too high, the farmer has the alternative of mixing his own fertilizers. These can be put together in the ratios which will best meet the requirements of each crop, assuming that these are known. If it is desired to prepare a mixture that will duplicate some analysis that is found on the market in ready-mixed form, it is necessary to be able to calculate the quantities of each material that will be required for this purpose. Since the analysis of a given fertilizer material may be reported in various terms, it is desirable to know how to calculate one from the other. The usual computations are those of changing from the element to the compound, as in determining the ammonia equivalent of a given amount of nitrogen. The factors in Table 147 are of value in this connection.



(a) (b)

FIG. 51. The cotton crop is a large consumer of fertilizer, and produces heavy yields of lint when liberally supplied with a well-balanced mixture. (a) 6-8-6 fertilizer. (b) No fertilizer.

The term "bone phosphate of lime" is frequently employed by the fertilizer trade. This is a synonym for tricalcium phosphate and is usually abbreviated to B.P.L. The phosphate content of bone, animal tankage, and phosphate rock is usually reported in this manner. Thus, a given grade of steamed bonemeal may be said to contain 61 per cent B.P.L. This is equivalent to approximately 28 per cent phosphoric acid. To calculate the amount of phosphoric acid (P_2O_5) in such cases, one has only to multiply the percentage of B.P.L. by the factor 0.46.

TABLE 147

FACTORS FOR CHANGING FROM FERTILIZER ELEMENTS TO COMPOUNDS

Nitrogen × 1.215	= ammonia	NH_3
Phosphorus × 2.288	= phosphoric acid	P_2O_5
Potassium × 1.204	= potash	K_2O
Calcium* × 0.399	= lime	CaO
Magnesium* × 1.658	= magnesia	MgO
Sulfur* × 2.500	= sulfuric acid	SO_3
Calcium* × 2.496	= calcium carbonate	$CaCO_3$
Magnesium* × 4.112	= calcium carbonate	$CaCO_3$
Ammonia × 0.823	= nitrogen	N
Phosphoric acid × 0.437	= phosphorus	P
Potash × 0.830	= potassium	K
Lime × 0.715	= calcium	Ca
Magnesia × 0.608	= magnesium	Mg
Sulfuric acid × 0.400	= sulfur	S
Lime × 1.784	= calcium carbonate	$CaCO_3$
Magnesia × 2.480	= calcium carbonate	$CaCO_3$

* Of importance chiefly in connection with the use of materials to control the soil reaction.

Assuming that a farmer is to mix a 4–8–8 analysis, he would ordinarily purchase nitrate of soda or sulfate of ammonia, superphosphate, and muriate of potash, and mix them in the proportions shown in Table 148.

TABLE 148

INGREDIENTS FOR 1 TON OF 4–8–8 FERTILIZER

Carrier	Compound	Per Cent	Pounds
Sulfate of ammonia	N	20	400
Superphosphate*	P_2O_5	20	800
Muriate of potash	K_2O	50	320
Dolomitic limestone†	....	....	480
Total			2000

* The large fertilizer mixers would substitute ammoniated superphosphate (2½–17–0) for the ordinary superphosphate and reduce the amount of sulfate of ammonia in the mixture.

† Added to overcome the acid effect of sulfate of ammonia.

The above fertilizer mixture should be used the same day it is made, for it will become hard on standing. The fertilizer manufacturer gets around this difficulty by allowing his sulfate of ammonia-superphosphate mixtures to cure in large piles, after which they are ground, mixed with the other materials required to make a complete fertilizer, and bagged. As a further precaution against caking, it is common practice to add organic materials to the mixture at bagging time. Calcium cyanamide is frequently used as a conditioning agent and as a source of lime to overcome acidity. If additional lime is required to make the mixture neutral, it is usually supplied in the form of dolomitic limestone, this being much less reactive than the high-calcium stone.

HIGHER-ANALYSIS MIXED FERTILIZERS

By reason of the high cost of transporting such heavy materials as fertilizer from the factory to the farm, it seems desirable to increase their concentration and reduce the quantity that would otherwise be applied. This is particularly important because of the ever-increasing amounts that are being used. It is not uncommon for potato growers and truck farmers to apply as much as a ton of fertilizer to an acre. If one considers such an analysis as a 4–8–8, these ratios could be prepared in much higher-percentage analyses, if it were so desired. Thus it is possible, by using somewhat more concentrated materials, to prepare a 5–10–10, a 6–12–12, an 8–16–16, and even higher analyses in which the ratios of the fertilizer compounds remain constant. The mixture in Table 149 may be made by either the farmer or the fertilizer manufacturer from materials that are now available in quantity, and would be of excellent mechanical condition.

TABLE 149

INGREDIENTS FOR 1 TON 8–16–16 FERTILIZER

Carrier	Compound	Per Cent	Pounds
Urea	N	42	381
Treble-superphosphate	P_2O_5	45	711
Muriate of potash	K_2O	50	640
Dolomitic limestone*	....	....	268
Total			2000

* To be neutral, this mixture should contain 400 pounds of limestone.

Still higher-analysis mixtures than the above may be produced by the use of urea, ammonium phosphate, and potassium chloride. In fact, if desired, a 12–24–24 analysis, and even higher analyses of the same nutrient ratios, can be produced from fertilizer materials which are available for use. These highest-analysis mixtures are strongly acid and contain little or no calcium sulfate. They should be used only on soils abundantly supplied with lime.

THE USE OF SINGLE FERTILIZER SALTS

It is possible that with the development of the more intensive and specialized systems of farming it may be found desirable to utilize the several materials at different periods in the growth of the crop.

Thus, in orchards and vineyards it has been found to be good practice to apply some readily available carrier of nitrogen early in the spring season, while phosphoric acid and potash fertilizers are supplied at some other convenient time for the benefit of the mulch or cover crop. Similarly, wheat is topdressed with nitrogen fertilizers in the spring, while the other fertilizers are applied at the time of seeding in the autumn. Market gardeners usually apply complete fertilizers to the soil before planting the crop, and later apply additional nitrate of soda as required. Usually only the nitrogen fertilizers are employed for topdressing purposes, but it is often desirable also to add either superphosphate or a carrier of potash to the soil after the crop was well started, the time of application depending upon the nature of the soil, the weather conditions, and the well-being of the crop.

By far the most common practice over a large portion of the general farming area of America is that of confining the fertilizer to some carrier of phosphoric acid and then depending upon the air for nitrogen and upon the soil for potash. This is especially true in the extensive grain-growing regions and in those areas in which dairy farming is being practiced. In general, however, as the intensiveness of the agriculture of any area increases, a greater need for nitrogen and potash develops, and complete fertilizers are employed. Thus, complete fertilizers are usually employed in the eastern and southern states; phosphate and potash mixtures are more popular in the eastern central states; and superphosphate, bone meal, basic slag, and phosphate rock are the only fertilizers that are employed over large areas of the Corn and Wheat Belts farther west. A rise in the selling price of farm products or a reduction in the cost of fertilizers is usually followed by a very marked increase in the tonnages of fertilizers that are used and by a change from superphosphate to complete mixtures.

The continued use of any single fertilizer or liming material to the exclusion of the others tends toward a relative accumulation of the elements contained in that material. As a result, unless care is taken to insure the presence of adequate amounts of the other elements that are required by crops, the single material applied will eventually become ineffective. Thus, while nitrogen can be taken from the air, and the soil and subsoil may be made to yield up considerable amounts of potash, yet, on all but the best-managed livestock farms, a time soon arrives when superphosphate alone is less effective than are fertilizers containing nitrogen and potash as well. This is an explanation for the alternate waves of popularity and disfavor which liming materials, landplaster, nitrate of soda, sulfate of ammonia, and superphosphate have experienced.

THE ADDITIVE EFFECTS OF FERTILIZER SALTS

Theoretically, the addition of a fertilizer salt to a soil should not result in an increase in crop yield unless that salt supplies an element in which the soil is known to be deficient. However, this theory neglects to take into consideration two facts, viz.: fertilizer salts may have more than one function in the plant; and they may affect the plant indirectly as a result of some reaction in the soil that is occasioned by their application. It is of interest to note that the relative amounts of the several fertilizer salts employed in the various countries are somewhat proportional to the quantities of these salts that are available for use in those countries. Thus Germany uses very large amounts of potash salts, Chile uses more nitrates, while the United States is a heavy consumer of phosphates. Similarly, large quantities of liming materials are often used in areas in which they are abundant and relatively cheap, whereas in other areas little or none of these materials is applied to the soil, entire dependence being placed on fertilizers.

Fertilizer salts have more or less additive effects on crop yields. This is indicated in Table 150 in the data from tests on Wooster silt-loam soil. These tests have been carried on since 1894. The land was systematically tiled at the beginning of the test. Lime has been applied as required. The rotation is potatoes, wheat, and clover. No manure has been added to the soil since the test was begun. Some difficulty has been experienced with potato diseases, but the data have a comparative value.

TABLE 150

Acre Increases* from Use of Fertilizer Salts (Thorne)

Fertilizer	Pounds	Potatoes	Wheat	Clover
Superphosphate	320	6.45	6.43	3.37
Muriate of potash	200	16.30	1.76	1.23
Nitrate of soda	240	6.65	1.12	3.76
All three	760	31.55	9.70	6.54

* Increases in bushels per acre of potatoes and wheat and of hundredweight of hay, as an average for a 30-year period.

It is not the purpose at this time to consider the ratios of several fertilizer materials that are best suited to the needs of the above crops, but simply to call attention to their somewhat additive effects. Muriate of potash was most effective on the potato crop, but superphosphate and nitrate of soda also aided in increasing yields, either when applied alone or in addition to the potash salt. Undoubtedly, it would be possible to select ratios and quantities which would be more suitable for use on the above crops and which would result in larger yields and more economic returns.

FIG. 52. Bent-over heads of wheat are a sure sign of high yields — the reward from the liberal use of fertilizer.

THE GROWTH OF THE FERTILIZER INDUSTRY

Similar data bearing on the effect of fertilizer salts on crop yields can be found at almost every experiment station in America. As a result, the fertilizer industry has become established and has for its purpose the supplying of these fertilizer salts in ratios to meet the requirements of the several crops, depending upon the nature of the crop plants themselves and upon the soil, climatic, and economic conditions that obtain. Of interest in this connection are the data in Table 151 which show the estimated tonnages of fertilizer materials, both mixed and unmixed, that were consumed in the United States in the years indicated. Data for a few representative states are also included for comparison.

TABLE 151

TONS OF FERTILIZER CONSUMED IN THE UNITED STATES

Year	U. S.	Georgia	Mass.	Ohio	Iowa
1912	5,981,000	1,103,000	48,000	151,000	2,500
1914	7,367,000	1,282,000	54,000	203,000	4,200
1915	5,586,000	872,000	56,000	225,000	5,100
1920	7,669,000	1,072,000	61,000	300,000	2,000
1925	7,464,000	778,000	62,000	321,000	2,100
1930	8,220,000	928,000	66,000	327,000	24,500
1935	6,273,000	617,000	63,000	306,000	5,000
1937	8,194,000	866,000	74,000	362,000	8,500
1938	7,504,000	768,000	69,000	324,000	11,100
Sq. mi.	2,973,774	59,265	8,266	41,040	55,586

The rapid growth of the fertilizer industry is assured. Many of the problems that are of greatest importance in the economical use of fertilizers remain to be solved. Some of these have been suggested previously and others will be discussed in the chapters to follow. Apparently farmers are convinced that the various materials that enter into the fertilizer mixtures perform useful functions in the soil and crop which are reflected in the larger yields that can be produced by their use. The rapid increase in fertilizer consumption during the first World War, the gradual increase in tonnage following the post-war period of depression, and the fact that farmers in Iowa are beginning to

TABLE 152

POUNDS OF PLANT NUTRIENTS USED PER ACRE IN 1936*

Country	N	P_2O_5	K_2O	Total
Netherlands	24.7	37.7	36.6	99.2
Belgium	28.5	27.9	23.8	80.3
Germany	15.6	20.1	31.1	66.9
Denmark	10.2	18.9	10.6	39.8
Norway	5.9	12.3	10.8	29.1
Sweden	5.2	10.2	6.3	21.8
France	4.0	10.7	6.0	20.7
Italy	4.2	11.8	0.5	16.7
Great Britain	2.4	7.0	2.9	12.4
United States	1.3	2.4	1.4	5.2
Poland	0.7	1.3	0.9	3.0
Hungary	0.1	0.8	0.0	1.0

* On cropped land. Figures compiled by the National Fertilizer Association.

experiment with fertilizers indicate the enormous possibilities for the development of this industry.

FERTILIZER PRACTICE IN OTHER COUNTRIES

European countries use fertilizers in much larger amounts than the United States. In fact, fertilizer practice was begun as a result of the investigations and teachings of Liebig, in Germany; of Lawes and Gilbert, in England; and of Ville and Boussingault, in France. In most of these countries fertilizer materials are purchased in unmixed forms and the mixing is done on the farm or the materials are applied separately as required.

The only countries in which agriculture has been carried on successfully over a long period of years without the use of fertilizers are China and Japan and some of the countries in the interior of Europe, of which Rumania is a frequently cited example. In Japan, the practice of using fertilizers has grown very rapidly during recent years. In both China and Japan, human excrement of the cities is carefully saved and hauled out to the fields. An enormous expenditure of labor is required in the making of composts from canal mud and green manures. Some idea of the laborious processes that are involved and of the economies that are necessary may be secured by reading the book entitled "Farmers of Forty Centuries," written, after personal investigation of the practices of Chinese and Japanese farmers, by King (see references at the end of the chapter). The explanation of Rumanian independence of fertilizers apparently lies in the natural productivity of the soil and in the economy of the practices that are followed. The difference between the practices of these countries and of those countries in which fertilizers are employed in liberal amounts is one of method and not of principle.

RÉSUMÉ CONCERNING MIXED FERTILIZERS

Fertilizer materials can be bought as such or in mixtures prepared in the fertilizer factory. In Europe, the common practice is to buy the materials and often to apply them separately. In America, fertilizers are bought already mixed unless it becomes necessary to topdress with nitrate of soda or unless only one fertilizer compound is required. Fertilizer inspection, under the direction of control chemists, protects both the producer and the consumer against fraud. The chief analytical problem that is involved is in the control work in connection with nitrogen. It is difficult to determine the quality of the nitrogen in organic materials. Fortunately, a larger proportion of fertilizer nitrogen is made from readily available inorganic sources each year.

The tonnage of fertilizers is gradually increasing. Large areas of land are being farmed on which no fertilizers are yet being used; but even those who farm the newer lands of Iowa and Kansas are beginning to experiment with fertilizers. Ultimately, with more intensive farming, the tonnage of fertilizers used in this country can be expected to reach a very high mark, as compared with the somewhat less than 8 million tons that are now being employed. This is indicated by the fact that intensively farmed countries, like Germany and the Netherlands, are now using from twelve to thirty times as many pounds of fertilizer to an acre of cultivated land as is being used in the United States, and that large areas of land in this country are still to be brought under cultivation.

Much higher analyses of fertilizers than are now used may ultimately be produced. Synthetic nitrogen compounds, superphosphates, and concentrated salts of potassium are available, from which analyses can be made that contain as much as 60 per cent of nitrogen, phosphoric acid, and potash, combined, as compared with the 16 to 20 per cent mixtures commonly employed. A great many problems are involved in the correct use of fertilizers, but the facts that enormous deposits of raw materials are available and that the fertilizers which are made from them can be used with remarkable and continued effectiveness guarantee the continued increase in the productive capacity of the soils of this country as long as the climatic factors remain unchanged in their average effects.

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CHAPTER XXV

THE SELECTION OF FERTILIZERS

As previously indicated, practically all soils that have been under cultivation for twenty-five years or more may have their productive capacities improved by the use of well-chosen fertilizers. Usually, the carriers of nitrogen, phosphorus, potassium, and calcium are somewhat additive in their effects, so that by their combined use the yields of crops may be raised to a very high level. The problem before the farmer is that of deciding on the ratios of these elements that are best suited to his needs and on the quantities of fertilizer to apply. It is evident that the soil, the climate, and the crop must receive consideration in reaching a decision. There is also an economic problem involved which may make it necessary to sacrifice yields for profit. The economic factors may determine not only the amounts to be applied but also the ratios of the several elements in the fertilizer mixture.

THE SOIL FACTORS

Certain general principles govern the choice of fertilizers in so far as this is related to the character of the soil. Chemical analyses checked by many fertilizer tests have shown that most of the soils of the United States are relatively deficient in phosphorus. The most important exceptions to this general statement occur in those areas in which deposits of phosphate rock are found, of which the bluegrass region around Lexington, Kentucky, and certain similar areas in Tennessee are notable examples. Muck and peat soils are usually very high in their content of nitrogen, but quite often contain only relatively small amounts of potassium. Acid peats are also deficient in available phosphorus. Soils of sandstone and shale origin usually contain very little carbonate of lime even though they are relatively young. Associated with this condition is a reduced availability of the nitrogen and of the mineral nutrients. Sandy soils are usually very low in their content of all the nutrients. This is particularly true of beach sands, which are often made up almost entirely of particles of pure quartz. A further general statement of principle is that in proportion as the rainfall is great and much leaching occurs, all soils become deficient in mineral nutrients no matter what may have been the nature of the original rock from which they were derived.

THE SYSTEM OF SOIL MANAGEMENT

The management of the soil, as related to the system of cropping and the method of disposal of the crops, is of primary importance in determining the extent to which the natural resources of the soil must be supplemented with fertilizer and liming materials. The well-known beneficial effects of legumes in aiding in the conservation and accumulation of nitrogen in the soil make it essential to take into consideration the frequency with which such crops appear in the rotation. If the crops that are grown are fed on the farm and the manure is carefully saved and applied, the losses of mineral nutrients and of nitrogen are much less than would be the case if all of the crop were sold as such. If, in addition, supplemental feeds are purchased and used, the productivity of the soil may be maintained at a high level, and the expenditures for fertilizers may be confined to that which is necessary to maintain the proper ratios of the nutrient elements. In grain farming, it is possible to have a system of soil management which corresponds in its effectiveness to that of livestock farming, by growing legumes to be plowed under and by returning the straw and stover of the grain crops to the soil.

In contrast with the above systems of farming and soil management are those that are followed in much of the corn- and cotton-producing areas. The most extensive use of fertilizers is found in the southern states, where a large percentage of the cropped land is devoted to corn or cotton every year, and where, in addition, the legume crop that is occasionally grown is usually cowpeas or soybeans — crops which do not contain as much organic matter, nitrogen, and mineral substance in their residues as do the clovers and alfalfa. With such systems of soil management, the losses by leaching and erosion are much more serious and the returns to the soil in the forms of manure and legume residues are much less.

Of particular interest in this connection is the system of farming followed in truck-farming areas, where continuous cropping to cultivated crops is the rule. Ordinarily, the land is not available for soil-rejuvenating crops except during short periods of the year. The problem was satisfactorily solved by the use of large amounts of city manure as long as these were available. The substitution of a combined fertilizer and green-manuring program seems now to be necessary.

THE CLIMATIC FACTORS

The various factors that influence the rate of growth of plants are interesting in their effects. Of these factors, the climatic group is highly important and has a controlling influence in the distribution of crops. Temperature and rainfall, particularly the rainfall-evaporation ratio, operate as limiting factors in crop growth at either extreme. If all the other factors are at the optimum, higher temperatures, within certain limits, increase the rate of biological activities both in the soil and in the plant. Chemical reactions ordinarily double their rate for every increase in temperature of 10° C., although no such rate of increase with rising temperatures is noted in the growth of plants. However, many of the biological processes in the soil are much more rapid under moderately warm conditions, provided they are not held in check by the lack of water or by some other limiting factor. This is well shown in Table 153, in which the relationship between temperature and nitrate accumulation is recorded.

Pennsylvania Agr. Exp. Sta.

FIG. 53. It is evident that the soil, the climate and the crop must receive consideration in reaching a decision as to the fertilizer analysis to use. There is a further economic problem involved which may make it necessary to sacrifice yields for profit.

Consideration of these and other similar data indicates that nitrogen fertilizers are likely to be much more effective under average conditions in the latitude of Wisconsin or Georgia than in the latitude of Illinois. In the northern states, the soil does not warm up so early in

TABLE 153

RELATION BETWEEN TEMPERATURE AND NITRATE ACCUMULATION (RUSSELL)

Temperature, Degrees C.	Nitrates Accumulated, in Parts per Million			
	7 days	14 days	21 days	28 days
5	1.3	3.2	7.2	8.9
15	5.4	7.5	11.5	11.0
25	7.6	11.5	18.1	21.2
35	13.8	16.9	31.1	36.2
45	6.1	12.4	17.3	23.2
55	0.4	−0.5	−0.7	....

the spring and the seasons are short. Nitrification, therefore, is delayed and is not likely to be excessive. Quite the opposite is true in the southern states, where the greater nitrogen loss could undoubtedly be compensated for by an increased rate of nitrogen fixation, under conditions in which advantage is taken of the more rapid rate of growth of leguminous crops that also takes place.

Phosphatic fertilizers have been found to be especially effective in hastening the maturity of crops. This may be objectionable with certain crops during dry seasons if maturity takes place before there has been adequate rainfall to meet the requirements for a satisfactory yield of crop. In northern latitudes, early maturity may be an advantage in avoiding damage to crops from frost. In more southern latitudes, the danger of drought is greater than the danger of frost. Potash salts seem to be especially effective in dry seasons by inducing a longer period of growth so that maturity is not attained until adequate rainfall has occurred. This is particularly important with a crop like corn which produces only one crop of ears. It is not of so much importance with cotton since this crop continues to produce bolls throughout the season and is prepared to take advantage of the needed moisture whenever it happens to rain.

In regions of sparse rainfall and in dry seasons in regions of humid climates, the use of large amounts of soluble fertilizer salts may increase the rate of growth and transpiration of crops to such an extent that the lack of water becomes a serious limiting factor. Thus, the use of a ton of readily soluble inorganic fertilizer salts on an acre of land in Kansas might have disastrous effects; but in Aroostook County, Maine, even larger amounts may be applied to advantage. These climatic differences make it necessary also to consider the quality of fertilizer materials. Organic materials yield up their nutrients somewhat in proportion to the weather, while readily soluble inorganic types produce an immediate effect on the concentration of the soil solution. Consideration must also be given to the ratios of the nutrient elements in the fertilizer, since each element has its specific effect as related to the rate of growth of the plant and to its maturity. This is one reason why the fertilizer recommendations, even for the same crops and for soils of similar characteristics, differ so markedly in the various states.

THE SOIL IN RELATION TO CLIMATIC FACTORS

As previously stated, the nature of the soil, both as to its physical and chemical characteristics, is more dependent on the climate than on any other group of factors. In those regions in which the rainfall is relatively limited, the only losses of plant nutrients from the soil may be those that are occasioned by crop removal. As the rainfall becomes greater, the leaching losses increase until a point is reached at which the removal of the nutrient elements in crops may be less than that which takes place in the drainage waters. If it happens that the soil is of such a nature as to have very little adsorbing power for any of the fertilizer elements and if the rainfall is heavy, the problem becomes increasingly complicated. The coastal plain sandy soils present this type of problem. The choice of fertilizers and the quantity to be applied, therefore, will be determined by the needs of the crop in one instance; by the additional factor of the adsorptive power of the soil in others; and, in the absence of any such adsorption, by the dissolving capacity of the drainage water that passes through the soil and runs off its surface.

A further complication is caused by soil erosion. The rate of removal of the surface material depends on the rainfall and on the slope of the land. In any case, subsoil is gradually being made into soil. If this rate is relatively rapid, deficiencies in nitrogen, phosphorus, and sulfur may always exist since these are present in the organic materials that are found in largest amounts in the surface soil. To continue to change subsoil into productive surface soil requires the use of large amounts of complete fertilizers. If some system of cropping that will keep this type of land adequately covered with vegetation during a large portion of the time is not adopted, such areas will ultimately be ruined for agricultural purposes.

THE CROP FACTOR

It is well known that the various species, varieties, and strains of plants vary in their nutrient requirements. This is indicated by the fact that plants are found to contain very different amounts of the several soil elements per unit of dry weight or per acre of produce. There is an additional complication in that they differ considerably in the spread and character of their root systems and consequently in their capacities to secure materials from the soil. Furthermore, some plants apparently are able to grow and thrive on a very low plane of concentration of the nutrient elements. These differences were noted in connection with the analyses of plants recorded, in the consideration of the variations in their lime requirements, and in the discussion of the relative feeding powers of plants for phosphate rock and feldspar. It is a well-known fact that some crops respond much more markedly to the use of fertilizers, or to one or the other of the several salts of which fertilizers are made, than do others. A tentative classification of crops according to their response to fertilizers follows:

TABLE 154

Response of Crops to Fertilizer Elements (Hartwell)

Group	Nitrogen	Phosphorus	Potassium
Least Response	Rye Bean Corn Cucumber Cabbage Pea Potato	Carrot Buckwheat Millet Oat Pea Bean Tomato	Corn Rye Cabbage Turnip Bean Oat Pea
Medium Response	Wheat Sunflower Turnip Tomato Beet Carrot Oat	Corn Potato Rye Wheat Sunflower Barley Lettuce	Millet Wheat Buckwheat Carrot Potato Tomato Barley
Greatest Response	Millet Parsnip Buckwheat Lettuce Barley Squash Onion	Cabbage Beet Cucumber Onion Parsnip Squash Turnip	Squash Sunflower Beet Onion Parsnip Lettuce Cucumber

There is little reason to believe that the above grouping holds when the crops are grown under ecological conditions different from those at the Rhode Island Agricultural Experiment Station, where the data on which these ratings were based was obtained. This is merely one detail of a map, concerning fertilizer effects, which will ultimately be constructed from the observations of the agronomists of all the experiment stations, when the observations are complete. A number of states are now attempting to standardize their fertilizer programs by taking into consideration the data from their experiment stations, the accumulated experiences of their farmers, and various types of indirect evidence bearing on this problem.

THE ECONOMIC FACTORS

In addition to the soil, crop, and climatic factors, consideration must also be given to the various economic factors that are involved in the choice of the analysis and in the determination of the quantity of fertilizer to apply. The relative cost of the several fertilizer elements has an important bearing upon the analysis. The total cost of the fertilizer and the selling price of the crop determine the quantity to apply. There is also the problem of deciding whether to depend upon the biological processes of nitrogen fixation and to adopt the livestock system of farming, or to depend upon the fertilizer bag for a large part of the necessary nutrients to compensate for the losses by drainage and crop removal.

In the growing of the grain and forage crops, investments in fertilizers are relatively small, as a rule, since the acre value of these crops is ordinarily too low to permit using as much fertilizer as is required for maximum yields. This is particularly true because large acreages of land that still retain much of their virgin productivity are being farmed in the United States. It also happens that the combination of grain and livestock farming, with the consequent growing of clover and use of manure, is very well suited for making the necessary adjustments demanded, owing to fluctuating prices of grain and livestock products. Thus, a large percentage of general farmers depend chiefly upon some carrier of phosphoric acid and purchase nitrogen and potash in variable amounts, depending upon their cost and the selling price of the products from the farm.

In the growing of the more specialized crops, such as potatoes, tobacco, sugar beets, and particularly the market-garden and truck crops, large amounts of fertilizer are applied. The reason is that there are opportunities for profit from their use because of a greater yield, a better quality of product, or the possibility of getting the crop to market at an earlier date. The relationships between the acre value of crops and the possible returns from the use of fertilizers are indicated in the following table. In these data, the assumption is made that a

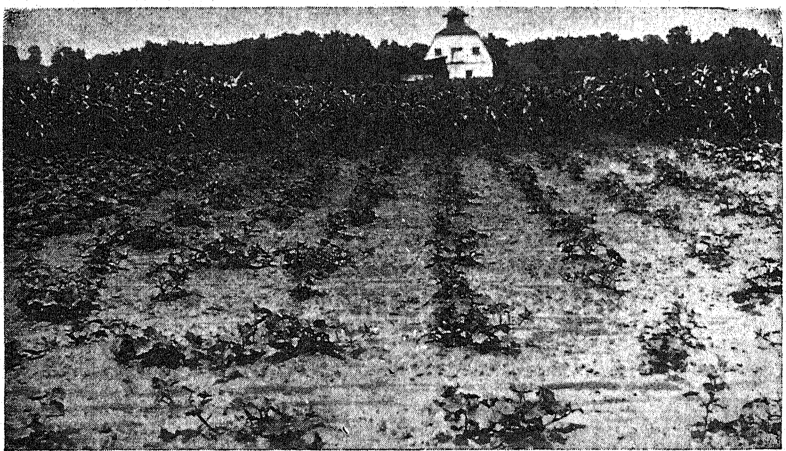

FIG. 54*a*. No fertilizer.

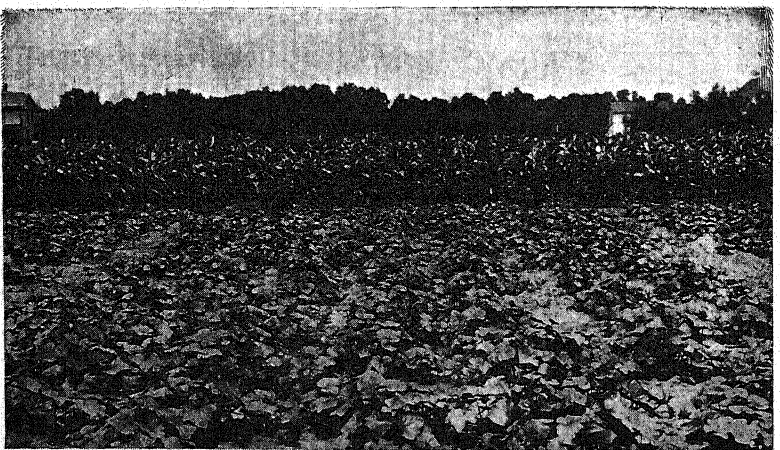

FIG. 54*b*. Complete fertilizer.

In the growing of the more specialized crops little attention is paid to the bank-account method of calculating the necessary return of mineral elements and nitrogen, but large amounts of complete fertilizer are supplied since there is opportunity for additional profit either by reason of a greater yield, a better quality, or the possibility of getting the product on the market earlier than most competitors. These are cucumbers on Ohio Experiment Station Farm at Marietta.

40 per cent increase in crop yield will result from the use of the fertilizer. The last column shows the number of pounds of fertilizer, costing $25 a ton, which could be purchased from the proceeds of sales of the 40 per cent increase of each crop.

TABLE 155

ACRE VALUE OF CROPS AS RELATED TO EXPENDITURES FOR FERTILIZERS

Crop Grown	Acre Yield*	Dec. 1 Price*	Acre Value	40% Increase	Fertilizer, Pounds†
Corn	28	$0.55	$ 15.40	$ 6.16	493
Wheat	14	1.00	14.00	5.60	448
Oats	33	0.31	10.23	4.09	327
Potatoes	123	0.53	65.19	26.08	2086
Tobacco	897	0.20	179.40	71.76	5740
Cotton	264	0.08	21.12	8.45	676

* Average yields, in bushels or pounds, and average selling prices in the United States for the year 1937.

† The number of pounds of fertilizer costing $25 per ton that could have been bought from the proceeds of sales of a 40 per cent increase in crop yields.

The data in Table 155 show that one could afford to buy and apply 2086 pounds of fertilizer costing $25 a ton to secure a 40 per cent increase in the yield of potatoes, at the selling price indicated, as compared with only 327 pounds of fertilizer in the yield of oats. The opportunity for profit in the use of fertilizers is greatest for tobacco, with which crop a 40 per cent increase in yield could normally be obtained from the use of less than one-third of the amount of fertilizer indicated.

National Fertilizer Association

FIG. 55. A yield of over 500 bushels of potatoes in Aroostook County, Maine, following the use of 1 ton of a 5–8–7 fertilizer per acre.

The quantity of fertilizer that can be applied to advantage to any given crop fluctuates with the selling price of that crop. This is very well shown in Table 156, in which are given the results of fertilizer

TABLE 156

SELLING PRICE OF CROP AS RELATED TO AMOUNT OF FERTILIZER (JORDAN)

Pounds Fertilizer	Acre Cost	Bushels Increase, Potatoes	Value of Increase above Cost	
			At $0.50	At $1.50
500	$ 6.25	23.3	$5.40	$28.70
1000	12.50	44.2	9.60	53.80
1500	18.75	55.4	8.95	64.35
2000	25.00	61.4	5.70	67.10

tests with potatoes. At the time this experiment was conducted, a 4–8–10 fertilizer, in unmixed materials, cost $25 a ton. The selling price of potatoes is subject to fluctuations ranging from less than $0.50 to more than $1.50 a bushel at the field. Assuming the given cost of fertilizer and selling prices of potatoes, the test indicates that a 1000-pound application is preferable at the former selling price, but that a 2000-pound application gives the greater return if potatoes are worth $1.50 a bushel.

DETERMINING FERTILIZER NEEDS OF SOILS

Preliminary to any careful laboratory tests that may be made, it is possible to detect certain nutrient deficiencies of soils by superficial examination in the field. Thus, sandy soils, those which are low in organic matter, and those soils that are acid in reaction, usually produce much larger crops if treated with a complete fertilizer. Muck and peat soils and those of limestone and chalk origin usually require the use of extra potash. The need for phosphoric acid is widespread, particularly on soils that are acid and have been subjected to the grain and livestock systems of farming for some years.

Black soils are usually high in available nitrogen, as are those which have been liberally manured and those on which a legume crop recently has been grown and plowed under. Soils of dry-land, irrigated areas usually contain an abundance of potash. Certain high-phosphate areas are known, such as the bluegrass region of Kentucky and Tennessee and the phosphate mining districts of Florida. Less phosphate is required on sandy soils than on soils of high-phosphate-fixing capacity, such as the heavier silt loams and clays. A knowledge of the system of soil management that has been employed throws additional light on the relative needs of the soil for the several nutrient elements.

TESTING SOILS FOR DEFICIENCIES

It is now generally recognized that it is possible, by examining a sample of soil in the laboratory, to determine its nutrient deficiencies. The difficulty with these tests does not lie in the laboratory procedures, but in the problem of selecting a representative sample from a given area or field. However, most of the agricultural experiment stations have established soil-testing laboratories, and some of the experiment station chemists have developed soil-testing kits which can be used by individual farmers.

These quick soil tests are especially helpful in deciding how much lime to apply and for avoiding the unnecessary expense of using nutrient elements where it is plainly evident that they are present, in available form, in liberal amounts. Interpretations of such tests often require considerable additional knowledge about the characteristics of the series of soils to which a given sample belongs and about the cropping and soil-management system which has been in operation on the land from which it came.

Soil tests are often supplemented by tests of the tissues of the growing crop. These tissue tests show whether the plants have actually been able to get sufficient amounts of each specific nutrient which they require. Tissue tests give an indication of the capacity of the soil to supply the crop with nitrogen and mineral nutrients and an indication of the extent to which the applied fertilizers have been delivered up to the crop.

FERTILIZER RATIOS

After soil tests have been made and consideration has been given to the past history of the field, one is then in position to choose a fertilizer containing nitrogen, phosphoric acid, and potash in ratios that are suitable to the needs of the soil and crop. The possible number of such fertilizer ratios is so large that steps have been taken to choose representative lists which include ratios of sufficient range to meet all the ordinary requirements. These lists vary from state to state, depending upon the soil and climatic conditions and upon the crops that are grown.

From time to time, efforts have been made to get agronomists and fertilizer producers to agree to confine their fertilizer recommendations to lists of analyses whose plant-food ratios are to be found on the intersecting points of what is known as a decimal fertilizer triangle. Such a triangle provides for 63 ratios, as shown in Table 157.

TABLE 157

POSSIBLE RATIOS BY USE OF DECIMAL FERTILIZER TRIANGLE

$N-P_2O_5$	$N-K_2O$	$P_2O_5-K_2O$	$N-P_2O_5-K_2O$			
1–9–0	1–0–9	0–1–9	1–1–8	2–2–6	3–4–3	5–2–3
2–8–0	2–0–8	0–2–8	1–2–7	2–3–5	3–5–2	5–3–2
3–7–0	3–0–7	0–3–7	1–3–6	2–4–4	3–6–1	5–4–1
4–6–0	4–0–6	0–4–6	1–4–5	2–5–3	4–1–5	6–1–3
5–5–0	5–0–5	0–5–5	1–5–4	2–6–2	4–2–4	6–2–2
6–4–0	6–0–4	0–6–4	1–6–3	2–7–1	4–3–3	6–3–1
7–3–0	7–0–3	0–7–3	1–7–2	3–1–6	4–4–2	7–1–2
8–2–0	8–0–2	0–8–2	1–8–1	3–2–5	4–5–1	7–2–1
9–1–0	9–0–1	0–9–1	2–1–7	3–3–4	5–1–4	8–1–1

PLANT SYMPTOMS OF SOIL DEFICIENCIES

Plants often show symptoms of soil deficiencies. Many of these are now recognized by agronomists and provide dependable clues on which fertilizer recommendations can be based. It is not feasible to describe any great number of these symptoms, but a few are given below.

A. Nitrogen deficiency indicated:

1. If the plants grow slowly and their leaves are yellowish.
2. If leaves of trees are shed prematurely.
3. If the lower leaves of corn tend to "fire."
4. If plants produce seed prematurely.

B. Phosphoric acid deficiency indicated:

1. If plants are stunted and leaves are pale green.
2. If cereals are slow to mature and to produce grain.
3. If yields of legumes are low.
4. If tomato and peach leaves have a purplish color.

C. Potash deficiency indicated:

1. If lower leaves of alfalfa are covered with small white spots.
2. If cotton leaves become reddish brown and die prematurely.
3. If potato leaves become puckered and curl under at edges.
4. If corn leaves fire along margins and green color between the veins fades.

D. Other nutrient deficiencies are indicated as follows:

1. Cracked stem of celery, brown rot of cauliflower, dry rot of sugar beets, heart rot of turnips, and corky core of apples indicate a need for boron.
2. Die-back in citrus and, on muck soils, blasting of onions and truck crops indicate a need for copper.
3. Pale-yellowish color of foliage, in the presence of adequate amounts of nitrogen and on soils that are high in lime or manganese, indicate a need for iron.
4. Sand-drown in tobacco, green veins with intervening purplish-red color on leaves of cotton, alternating green and white stripes on leaves of corn, and bronzing of citrus indicate a need for magnesium.
5. Pale-green to yellow and red colors between green veins of leaves of tomatoes and beets, resinous spots on leaves of citrus, and chlorosis of spinach on overlimed soil indicate a need for manganese.
6. Mottle leaf of citrus, rosette of pecans and walnuts, and white-leaved corn indicate a need for zinc.

Referring again to the decimal triangle system of selecting fertilizer ratios, one would expect that, as soils get older, their fertilizer needs would become quite similar and that the ratios required would be those that lie close to the center of the triangle, as represented below. This is normally true.

TABLE 158

THE FERTILIZER TRIANGLE

N
Only

9–0–1 9–1–0

8–0–2 8–1–1 8–2–0

7–0–3 7–1–2 7–2–1 7–3–0

6–0–4 6–1–3 6–2–2 6–3–1 6–4–0

5–0–5 5–1–4 5–2–3 5–3–2 5–4–1 5–5–0

4–0–6 4–1–5 4–2–4 4–3–3 4–4–2 4–5–1 4–6–0

3–0–7 3–1–6 3–2–5 3–3–4 3–4–3 3–5–2 3–6–1 3–7–0

2–0–8 2–1–7 2–2–6 2–3–5 2–4–4 2–5–3 2–6–2 2–7–1 2–8–0

1–0–9 1–1–8 1–2–7 1–3–6 1–4–5 1–5–4 1–6–3 1–7–2 1–8–1 1–9–0

K_2O Only 0–1–9 0–2–8 0–3–7 0–4–6 0–5–5 0–6–4 0–7–3 0–8–2 0–9–1 P_2O_5 Only

From among these ratios one might well select five complete ratios which would meet most of the requirements fairly satisfactorily. The ratios and their suggested uses follow:

(*a*) 5–3–2, on timothy meadows and on lawns and fairways.
(*b*) 2–6–2, on small grains and rice.
(*c*) 2–4–4, on corn, pastures, potatoes, and tobacco.
(*d*) 3–4–3, on cotton and vegetables.
(*e*) 2–3–5, on muck-soil crops such as onions and celery.

To any one of these could be added a supplemental topdressing or sidedressing of a nitrogen carrier once the crop had gotten under way, the quantity of this nitrogen carrier to be determined by the intensiveness of the farming, the acre value of the crop, and the use to which it is to be put.

These ratios would be sold in such analyses as manufacturers found it most economical to produce. Thus the 2–6–2 ratio can be sold as a 4–12–4, 5–15–5, 6–18–6, or 10–30–10 analysis, the farmer choosing the one which gives him the greatest value per dollar invested when applied to the field.

In addition to the complete fertilizer ratios suggested above, one might have need for a mixed fertilizer carrying only two of the nutrient elements. Thus, on muck soils or on those that had a legume crop plowed under, a phosphate-potash mixture might meet the requirements. For areas to the west where the climatic conditions are such that excessive leaching of bases from the soil has not taken place, a nitrogen-phosphate mixture might be entirely satisfactory. For regions in which the soils are high in their phosphate content, as they are in Central Kentucky and Tennessee, or for topdressing purposes on sandy loam soils where a high-phosphate fertilizer has been applied as a basic treatment, a nitrogen-potash mixture might meet the requirements.

TRENDS IN FERTILIZER PRACTICE

Virgin fertility of the better lands in the United States permitted of growing crops for a number of years with little consideration to the use of fertilizers. Gradually the original stores of nutrient elements became partly depleted. Crop rotations, including legumes, were then introduced. Some attention began to be paid to saving manure. Ultimately the manure spreader was developed as an aid in making the manure cover more land.

At first fertilizer practice consisted largely in the use of bone and land-plaster. Lime was found to be effective in increasing yields. Later superphosphate was introduced. Guano and potash salts were ultimately mixed with the superphosphate to make complete fertilizers.

As market gardening and vegetable growing became more important, the demand for manure increased. At first this was supplied from city stables. Later, when the automobile began to displace the horse, the supply of manure became inadequate. The use of green manures coupled with heavier applications of complete fertilizers became necessary.

As city populations continued to grow, more and more land had to be devoted to potatoes, fruits, sugar crops, tobacco, and a great variety of vegetable crops. This type of farming gradually replaced dairy and livestock farming on those areas especially adapted to these intensive crops. The rate of application of fertilizer increased until acre applications reached a ton or more.

With these heavy applications consideration was given to the possibilities of increased concentration. The popular 4–8–8 and 4–12–4 fertilizers contained some 80 per cent or more of material that was not known to have any special value. The question arose as to whether it might not be possible to double or treble the concentration and produce fertilizers carrying 40 or 50 per cent of the necessary plant nutrients.

Meanwhile the air-nitrogen industry was being developed. Processes were improved. Production was rapidly increased. New carriers of nitrogen were made available. The unit cost of nitrogen was materially reduced. It then became doubtful whether legumes were still the cheapest source of extra nitrogen. More fertilizer nitrogen, and more potash as well, began to be used. Acre production was materially increased on the better-farmed lands.

The world increase in fertilizer consumption, together with the development and use of improved agricultural machinery resulted in overproduction of food stuffs and other products of the farm. The farmer was faced with the necessity of lowering his production costs. This tended to force marginal land into forest and waste and to bring the better land under more intensive cultivation, in the fertilizer-using areas.

Even the dairy farmer found it to his advantage to concentrate his efforts on his better pasture land and to make use of fertilizers in the production of high-protein feed to be harvested without expense by the cows themselves. Hog farmers found phosphates, and later complete fertilizers, necessary to produce the needed corn. Beef cattle farmers found that the manure was more effective if reinforced by the use of superphosphate. The tractor displaced more and more horses, reduced the quantity of manure available, and forced the use of more fertilizer.

It is apparent from the above reasons that fertilizer practice has been changing and that it must continue to change. More is being used. Manure is being replaced. Legumes are no longer depended upon as the sole source of nitrogen. Farming is becoming more intensive.

Here and there a new fertilizer practice is tried. If it is successful the practice grows. For the man who is alert, there are many possibilities in the use of fertilizers that have as yet been realized by only a few of the most successful.

SOLUTION OF THE PROBLEM OF SELECTING FERTILIZERS

"The eye of the master fatteneth his cattle." So the eye of the farmer must determine finally what fertilizers meet his needs. The general principles previously stated are of value in reaching a decision on the relative amounts of the nutrient compounds which should be used. The experimental data from the nearest test farm are of considerable value. Supplemental tests with fertilizers may be conducted on each farm if time permits. The experiences of the other farmers in the community merit consideration. While theoretically there is only one analysis that will give the optimum yield for any given season, in practice this does not seem true. Somewhat less of any one element may be compensated for, as a rule, by more of another. This is indicated in the following table, which gives the average increases in acre yields produced by a number of fertilizers of different analyses on Wooster silt-loam soil at the Ohio Experiment Station.

TABLE 159

AVERAGE ACRE INCREASE IN YIELD FROM 1000 POUNDS OF FERTILIZER

Analysis	Corn, Bu.	Oats, Bu.	Wheat, Bu.	Clover, Cwt.
0–16–0	9.56	2.91	11.14	4.21
0–12–4	16.56	5.42	12.21	7.48
2– 8–2	11.03	4.89	12.49	7.14
2–12–2	15.36	7.11	15.18	11.41
4–12–2	16.22	6.21	14.29	11.96
4– 8–4	17.13	6.32	13.41	10.50
4– 8–8	20.02	6.66	14.36	10.56

The 2–12–2 and the 4–8–4 analyses are fundamentally different mixtures, yet the choice between the two lies in the matter of their relative cost rather than in their relative effectiveness. For a very marked deficiency of some one element, it may be necessary to make heavy

applications of this element. There is little justification for any large number of analyses. If sufficient range is available for meeting special needs, any desired analysis between the extremes may be made by combining two mixed fertilizers in the necessary proportions. There is a fundamental difference between mixing two mixed fertilizers and mixing fertilizer materials. In mixing two mixed fertilizers, the problem of condition does not enter; and, if the mixing should not happen to be thoroughly done, no particular difference would be noted in the effects since either mixture would probably have given satisfactory yields.

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CHAPTER XXVI

THE APPLICATION OF FERTILIZERS

In determining the time and method of application of fertilizers, consideration should be given to the nature of the fertilizer materials, the type of soil, the kind of crop, the climatic conditions, the nature of any other materials that are to be added to the soil and their time of application, and the economic factors that are involved. Thus, nitrate of soda is readily leached from the soil, while ammonia nitrogen is not. High concentrations of fertilizer salts cause more damage in sandy soils than in clay loams. The time to apply nitrogen fertilizers is determined in part by the nature of the crop and the product that is to be marketed. In areas of short growing seasons, hill applications of fertilizers may be especially important in giving the crop a start. Liming materials and phosphate rock should not be applied to the soil at the same time. Any method of fertilizer application that is inconvenient or requires an additional operation with some implement increases the cost of production of the crop.

FERTILIZER MATERIALS IN RELATION TO THEIR APPLICATION

Soluble phosphates are ordinarily fixed by the soil within a short time after they have been applied. Drainage waters carry such small amounts of phosphorus that there is little danger of loss of this element by leaching. In acid soils, precipitation as iron or aluminum phosphate occurs instantaneously as soon as solution of the phosphate takes place in the soil water. In soils that contain soluble calcium, the usual reversion to dicalcium phosphate ordinarily results. Similarly, potassium is not found in as large amounts in the drainage waters as the solubility of the salts of this element would lead one to expect. The potassium ion soon replaces some other cation in the exchange complex of the soil. In acid soils, the hydrogen is partly displaced. In soils that are approximately neutral in reaction, a corresponding salt of calcium or magnesium is usually lost in the drainage water as a result of the application of potassium sulfate or chloride to the soil.

The problem is somewhat more complicated with nitrogenous materials since these vary from insoluble organic substances to highly soluble inorganic salts. Of the inorganic salts, nitrates are not fixed by the soil, but the ammonium radical is readily adsorbed by the exchange complex in much the same way as potassium. Nitrate fertilizers, therefore, should be applied as needed. If delayed effects are desired, sulfate of ammonia or organic ammoniates are to be preferred.

From the above considerations, it is apparent that basic applications of phosphate and potash fertilizers, together with relatively small amounts of nitrate of soda, may be made to the soil at the time of planting the crop, while supplemental topdressings of nitrate of soda may be required from time to time as the season advances. If all the fertilizer is to be applied at planting time, sulfate of ammonia or organic ammoniates may well be substituted for part of the nitrate of soda in order to avoid excessive losses in the drainage water.

The use of large amounts of highly soluble salts may cause injury to germinating seeds or to young plants unless care is taken to effect their proper placement in the soil. Thorough mixing with the whole volume of plowed soil well in advance of planting lessens the danger but also reduces the effectiveness of the fertilizer. There is reason to believe that, where large amounts of fertilizer are to be used, a considerable part of it may well be placed on the bottom of the furrows at plowing time, the remainder being applied in bands along the row at planting time or being used in the form of a starter solution.

Heavy applications of kainit or of double manure salts are ordinarily made well before planting the crop in order that the soluble salts resulting from cation exchange reactions may be leached out or carried into the subsoil. Ammoniacal nitrogen added in advance of planting the crop may be changed to the nitrate form by the time it is required by the growing plants. Calcium cyanamide should be applied previous to planting in order that the toxic intermediate products of its decomposition in the soil may be changed to a harmless state.

SOIL TYPE IN RELATION TO FERTILIZER APPLICATION

Determinations of the optimum ratios and concentrations of the nutrient elements for plants when grown in culture solutions do not provide a reliable clue to the ratios in which the various fertilizer salts should be applied for optimum results in the field. This is because the soil exercises very marked fixation, adsorption, and exchange effects on the added nutrients which alter both the concentrations and the ratios in which the ions were added. In sandy soils these changes are least marked, since such soils are often made up in very large part of quartz grains which have little or no power to adsorb the nutrient ions. Not only is the nitrate ion likely to be leached from sandy soils, but considerable amounts of ammonium and potassium salts and even phosphates will also be found in the drainage water if they are applied in large amounts. Fortunately, most sands contain small quantities of inorganic colloidal matter in which, in large part, the exchange capacity of the soil lies. However, it is by reason of the lack of adequate amounts of clay and humus that sandy soils are very much improved in their crop-producing powers by the addition of large quantities of well-decomposed organic matter.

It seems probable that on sandy soils, which are very high in quartz and contain little colloidal matter, the fertilizer should be applied in small doses that are repeated frequently during the crop season, the time of these later applications depending upon when rain fell or irrigation water was supplied. In the absence of an adequate water supply, the fertilizer might well be applied in liquid form. Preliminary experiments along this line indicate important possibilities in this method of fertilizing crops.

It is also apparent that the use of large amounts of fertilizer, particularly in hill or row applications, is much more likely to cause injury to crops growing on sandy soils than to crops growing on silt loams, clay loams, and mucks. Not only do sandy soils have relatively small capacities to adsorb nutrients from the soil solution or to cause their rapid fixation, but they are also usually very low in their moisture content and toxic concentrations of salts may occur, particularly in times of drought. It is mainly because of this that florists use such large amounts of compost and leaf mold in their flower pots. Similarly, truck farmers use large amounts of manure or go to considerable trouble to plow under green manures and crop residues in order to protect their plants against too high concentration of salts in periods of drought.

THE CROP IN RELATION TO FERTILIZER APPLICATION

The protein content of plants can be increased by applying nitrate fertilizers to them just in advance of their maturity. Use is made of this principle in fertilizing timothy and in changing soft wheats to hard wheats. An example of the results of such use of nitrogen is shown below.

TABLE 160

EFFECT OF TIME OF APPLYING NITRATE ON PROTEIN* OF WHEAT (GERICKE)

Days after Planting	White Australian	Turkey Red
.....	8.9	14.6
17–21	9.2	13.8
33–36	10.6	14.7
48–60	11.4	13.4
72–81	13.0	14.3
109–110	15.2	17.9

* Protein expressed as per cent.

The soft spring Australian wheat was found to be quite similar in its characteristics to the hard winter Turkey red wheat, when nitrate of soda was applied 73 to 110 days after planting. The nitrate of soda was applied at the rate of 100 pounds to an acre, as a topdressing.

Fertilizers are often applied with or near the seed at the time of planting. Experimental tests indicate that injury to germination from excessive concentrations is more likely to occur with small seeds than with large ones. The following data are significant in this connection. In this test the fertilizers, in the amounts indicated, were scattered over the seeds in the bottoms of the furrows before these were covered with soil. Most marked effects were produced with air-slaked lime and with alfalfa and grass seeds. As would be expected from previous considerations, very little injury resulted from the use of superphosphate even in 300-pounds-an-acre applications when applied directly to the seeds in the row, but marked injury resulted from the supplemental use of nitrate of soda and muriate of potash.

Crops that have long growing seasons are quite likely to be benefited by supplemental topdressings of nitrate of soda or some other readily available source of nitrogen. This is particularly true if the soil is sandy, if the rainfall is heavy, and if the more readily available forms of nitrogen are used at the time of seeding. Thus, the second application for corn is made as a sidedressing when the plants are about knee-high; for winter oats or wheat, at the time of starting growth in the spring; and for cotton, during its early fruiting stage.

TABLE 161

EFFECT OF FERTILIZERS IN CONTACT WITH SEED ON GERMINATION* (HUTCHESON)

Seeds Tested	Air-slaked Lime, 4000†	Muriate of Potash, 200	Nitrate of Soda, 200	Superphosphate, 300	Complete Fer., 700	Check Seeds
Corn	81	96	96	98	98	96
Wheat	64	76	80	70	58	70
Rye	50	66	78	80	56	78
Oats	64	96	86	88	74	86
Soybeans	40	84	94	92	62	96
Alfalfa	0	26	56	58	14	84
Red clover	3	37	63	57	12	72
Timothy	7	24	51	77	40	41
Red top	8	63	76	77	26	70

* The figures are the percentages of seed which germinated.

† Pounds per acre.

With perennials, the normal procedure is to apply large amounts of phosphate and potash fertilizers at the time of seeding and to use supplemental topdressings of nitrate of soda annually as required. In seeding lawns, this principle is especially important. For strawberries, bush fruits, grapes, tree fruits, and timothy meadows, the same principle applies. Once these crops are well established in soils that are liberally supplied with available phosphoric acid and potash, annual topdressings of readily available salts of nitrogen at a rate of 100 to 300 pounds to an acre are all that may be required for a number of years for satisfactory results.

Some marked improvements in yields of special crops may be produced by using nitrate of soda at particular periods in the growth of these crops. An abundance of available nitrogen in the soil through the entire growing period of a crop often results in excessive vegetative growth at the expense of fruitfulness. It is desirable to give the crop suitable quantities of nitrogen for a satisfactory early rate of growth and then to apply supplemental amounts as topdressings at the fruiting stage. With apple trees, nitrate is added just before the blossoming period. With cabbage, the second application of nitrate of soda or sulfate of ammonia is made as a sidedressing just after the heads have started to form. For tomatoes, blossoming should take place under conditions of relative scarcity of nitrogen, but heavy applications of soluble nitrogen fertilizers may be made to advantage as soon as the fruit is set.

In the growing of root crops, excessive applications of nitrogen are likely to produce top growth at the expense of root development. Consideration of the principle of the nitrogen-carbohydrate ratio makes it appear probable that heavy applications of nitrogen fertilizers will result in excessive vegetative growth at the expense of root systems, but that quite the opposite effects may result in the case of nitrogen deficiency. Whether the tops are parasitic on the roots or the roots are parasitic on the tops depends upon the balance that is maintained with reference to the supplies of nitrogen and carbohydrates in the plant. This balance is very seriously disturbed by such practices as pruning fruit trees and grazing pastures. The use of nitrogen fertilizers has been largely substituted for the pruning of apple trees. Continuous heavy grazing of pastures robs the root systems of the pasture grasses of proper nourishment.

THE CLIMATE IN RELATION TO FERTILIZER APPLICATION

In proportion as the rainfall increases, losses of soluble materials from the soil are likely to be more serious. On sandy soils and under conditions of heavy rainfall, this requires that occasional dressings of soluble nitrogen fertilizers be made or that organic ammoniates be substituted for the inorganic salts if the entire application is to be made when the crop is planted. This explains the popularity of fish scrap and cottonseed meal in fertilizers used on sandy soils and in regions of high rainfall.

It is also evident that heavy applications of fertilizers are quite likely to be important in regions of cool climates and relatively short seasons. The processes of decomposition of organic matter and of nitrification are relatively slow until the soil temperature becomes fairly high. In order to give the crop a rapid start as a means of lengthening the season and getting ahead of the weeds, row or hill applications of fertilizers in sufficient amounts to meet the immediate needs of the crop are desirable. Most of the fertilizer may well be applied broadcast in order to raise the general level of productivity of the soil and to prevent the marked irregular growth that is often noted in the subsequent small-grain or hay crops when fertilizers are applied only in the row or hill. A disc drill, set deep, gives the best results.

In cool seasons, topdressings of nitrates are likely to be more effective than in warm seasons. Both nitrogen and potassium tend to lengthen the period of growth of the crop. In order to avoid prolonged vegetative growth of crops like corn in regions of short seasons, liberal applications of superphosphate are useful in hastening the maturity of the crop. In seasons of drought, the use of superphosphate alone may effect such rapid maturity of the crop as to place it in the critical stage of seed production before the much-needed rain arrives. Thus, crops of corn, wheat, tobacco, and potatoes have been reduced in yield by the use of superphosphate in dry seasons and in the absence of adequate amounts of available nitrogen and potash.

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FIG. 56. Effect of the row application of fertilizer for corn on the following crop of barley.

In regions of low rainfall and of high evaporation, large amounts of fertilizer salts cannot be applied to soils because of the excessive concentration of the soil solution that may thus be produced. It is not uncommon for potato growers and truck farmers of the Atlantic coast states and of the cooler and moister regions of the New England states to use a ton of high-analysis fertilizer on an acre. Such heavy applications of fertilizer would probably result in serious injury to crops in Kansas, Nebraska, and similar areas in which danger from drought is always imminent. Under such conditions, the crops may be overstimulated early in the season and may produce more vegetative growth than the subsequent rainfall will support.

Under conditions of dry weather, topdressings of nitrogen fertilizers are likely to be more effective, if they can be worked into the soil. In lawns or on truck crops, water can be applied to good effect. It is possible that a hygroscopic salt, such as nitrate of lime, may have an additional value under conditions of drought by reason of its self-dissolving power.

Phosphate and potash fertilizers, to be most effective, should be applied at some depth in the soil. Although a certain amount is needed in close proximity to the seed or young plant roots to be of immediate use, additional quantities may well be placed at considerable depths where the nutrients will be available to the roots later in the season when the surface soil is dry and the root hairs have largely disappeared from that portion of the soil.

Although row or hill applications of fertilizers do not necessarily result in the localization of the roots of plants, it has been shown that roots branch very profusely and become much more abundant at points at which they come in contact with fertilizer salts, particularly phosphates. It thus seems logical to place a considerable part of the fertilizer fairly deep in the soil in order that well-developed systems of feeding roots may be located below the depth to which the soil may dry out during periods of scanty rainfall in the summer season.

Of considerable interest in connection with the climatic factor is the fact that plants that are well supplied with fertilizer salts are less subject to injury from frost than those growing on soils that are low in their content of nitrogen and mineral nutrients. The data in Table 162 from experiments with corn plants indicate the efficiency of fertilizers in this respect.

The peat soil that was used in the above test was kept at its optimum moisture content. The fertilizer was applied in the hill at a rate of 170 pounds of 3–10–4 per acre. Such an amount of protection may be adequate to meet the requirements of plants as against the ordinary

TABLE 162

EFFECT OF FERTILIZERS ON FREEZING OF CORN PLANTS (MAGISTAD)

Temperature, °C.	Time, Minutes	Plants, Number	Plants Frozen, Percentage	
			Fertilizer	No fertilizer
−0.7 to −1.0	30	20	1.00	4.40
−0.8	40	8	1.00	5.00
−0.5 to −0.6	60	8	0.00	0.20
−1.0 to −3.0	120	20	19.00	49.00

frosts that occasionally cause damage to corn and other spring-planted crops. The osmotic concentration of the cell sap of the plants was shown to have been increased as a result of the use of the fertilizer.

LIMING THE SOIL IN RELATION TO FERTILIZER APPLICATION

The processes of nitrification in acid soils are hastened by the application of liming materials. Differences in the rate of availability of nitrates and ammonia salts tend to disappear if the soil contains adequate amounts of carbonate of lime. An application of lime often reduces the need for fertilizers by stimulating biological activities to such an extent that adequate amounts of nitrogen and mineral nutrients are released from the organic matter in the soil. Similarly, liming the soil tends to effect a displacement of the potassium in the exchange complex.

On the other hand, heavy applications of liming materials may reduce the availability of phosphorus and of trace elements in the soil. It has been noted that phosphate rock is relatively more effective on acid soil than on soils which have been limed. It would thus be well to apply limestone and phosphate rock at different periods in the rotation. A satisfactory method of applying phosphates is that of scattering them over the manure before it is hauled to the field, or applying them on the clover sod or sweet clover before these are plowed under for the cultivated crop. The decay of these materials liberates nitric acid, the effect of which may thus be largely concentrated on the phosphate to effect its increased solubility. The application of lime or limestone may then be delayed until the seeding of the small grain or immediately preceding the sowing of clover seed.

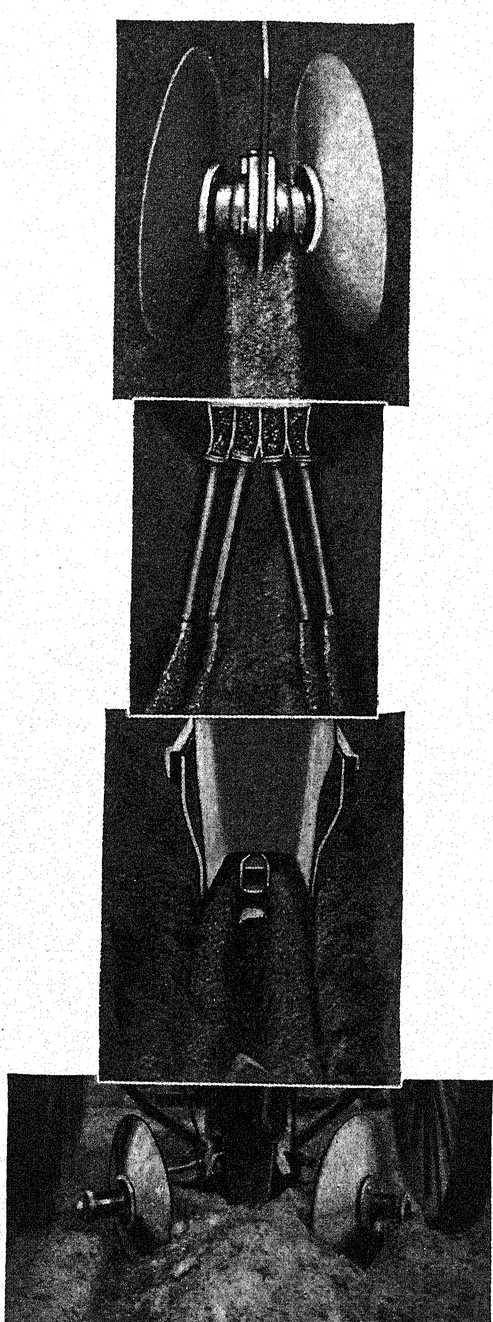
ECONOMIC FACTORS IN RELATION TO FERTILIZER APPLICATION

In the ordinary rotation of a cultivated crop, a small-grain or a legume hay crop, it seems logical to make relatively heavy broadcast applications of fertilizer to the small grain, both for its effect on the grain and on the other crops in the rotation and in order to limit the the fertilizer application to a small amount in the row or hill for the cultivated crop. Less extra labor is involved in this method of applying fertilizers, since in both cases the fertilizer is applied at the same time as the crop is being planted. Most of the fertilizer should probably be applied broadcast in order to raise the level of productivity of all of the soil and thus to avoid the unevenness that occurs in subsequent crops as a result of row fertilizer applications. With cultivated crops of high acre value, it may be profitable to apply part of the fertilizer broadcast and part of it in the row, even though the extra labor of the broadcast application is involved.

By reason of the present low cost, and possible still lower future cost, of fertilizer nitrogen, it seems desirable to consider the matter of using fertilizer nitrogen to supplement the usual limestone-phosphate-potash treatments on pastures. It has usually been assumed that the primary object in fertilizing pastures was to stimulate the growth of white clover, thus taking advantage of its nitrogen-fixing powers. However, by using nitrogen fertilizers one reduces the risk in growing grass, clover not always being dependable in dry seasons. The best procedure calls for combining both methods, stimulating the clover as much as possible by the use of limestone, phosphate, and potash, and using nitrogen fertilizers separately as a supplement, particularly for earlier pasture, and for more dependable pasture during periods of drought. Nitrogen-fertilized pastures must be properly grazed, otherwise the grass tends to shade the clover so that it crowds it out.

SPECIAL METHODS OF APPLYING FERTILIZERS

In placing the fertilizer with reference to the seed in row applications, there are several possible locations. These are indicated in the following table, showing the results of some experimental tests with potatoes on Carrington fine sandy loam soil, in which a 4–12–4 fertilizer was used at the rate of 1600 pounds to an acre. These and other data indicate that if the fertilizer is placed in contact with the seed, above the seed, or below the seed, injury is likely to result. The vertical movement of water tends to bring any soluble fertilizer that is placed above or below the seed in direct contact with the seed. Probably the best location for the fertilizer is at the sides of the seed with some intervening soil between and in a plane which is somewhat lower than that of the seed. Fertilizer that is placed too near the surface is not likely to be as effective, in average seasons, as is that



(*a*) *Opening plow.* The discs at the front of the machine open two furrows and leave a small ridge down the middle of the row.

(*b*) *Fertilizer tubes.* Two sets of fertilizer tubes carry the fertilizer from the hopper and deposit it in the furrows.

(*c*) *Planting shoe.* The planting shoe splits the ridge and covers the fertilizer, thereby making a groove into which the seeds are dropped, and eliminating all danger of fertilizer coming in contact with the seed.

(*e*) *Covering discs.* The discs at the rear cover the seed and the fertilizer is left properly placed along both sides of the row.

Emil Truog, Wisconsin Agr. Exp. Sta.

FIG. 57. If the fertilizer is separated from the seed, tuber, or root of a young plant by a thin layer of soil, injury can be avoided.

which is placed deeper but at such a point that some of it will soon be reached by the roots of the young seedlings.

TABLE 163

EFFECT OF METHOD OF APPLICATION OF FERTILIZER ON POTATO YIELDS* (COE)

At sides, lower plane, narrow spread	216
At sides, same plane, narrow spread	202
$\frac{1}{4}$ below seed, $\frac{3}{4}$ at side, narrow spread	200
$\frac{1}{2}$ in ridge ahead, $\frac{1}{2}$ at sides, narrow spread	200
At sides, same plane, wide spread	191
$\frac{3}{4}$ in ridge ahead, $\frac{1}{4}$ at sides, narrow spread	188
In made-up ridge ahead	183
$\frac{1}{4}$ above seed, $\frac{3}{4}$ at sides, same plane, narrow spread	183
Above seed, soil interposed, wide spread	165
Above seed, soil interposed, narrow spread	162
Check yields, no fertilizer	149
Mixed with soil in row	131
Direct contact in row	117

* Acre yields in bushels.

Experimental data for corn indicate that smaller applications of fertilizer in the row are likely to be somewhat more effective than larger amounts applied broadcast. However, the amount thus applied must be quite small, unless it is composed entirely of phosphates which have relatively little effect on the concentration of the soil solution. A layer of soil between the fertilizer and the seed, and placing the fertilizer at the side rather than above or below the seed, are important conditions to be met.

RÉSUMÉ CONCERNING THE APPLICATION OF FERTILIZERS

In general, phosphate and potash fertilizers may be applied in relatively large amounts and less frequently than nitrogen fertilizers are applied. Where heavy applications of nitrate are used it is usually best to apply only part of the fertilizer when the crop is planted and to add the remainder from time to time as required. If this is not desirable, then ammonia salts and organic carriers of nitrogen should be substituted for part of the nitrate.

In regions of high rainfall in warm climates with long growing seasons and for sandy soils, the losses of fertilizer constituents in the drainage water are likely to be quite heavy. This is especially true of nitrogen fertilizers, but may also hold for phosphate and potash fertilizers as well. Under such conditions, fertilizers should be applied only as required by the immediate crop and not in large amounts on only one of several crops that may be grown in the rotation.

Small amounts of fertilizer in the row or hill are sometimes as effective as much larger amounts applied broadcast. The young plant roots come into contact with the fertilizer early in their life history and are thus stimulated to rapid growth without delay. Under such conditions, the fertilizer should be placed a short distance away from the seed, preferably at the side, and in a plane that is somewhat below that of the seed. Part of the fertilizer may well be applied with a drill at considerable depth in order that it may be available for the use of the plant roots later in the season when the surface soil may be rather thoroughly dried out.

Especial care must be taken in sandy soils by reason of the very low moisture content of such soils and their relatively small adsorptive capacity for soluble ions. Similarly, heavy applications of highly soluble fertilizers are to be avoided in regions of low rainfall and of high evaporation. As a precaution against excessive concentrations of salts in a sandy soil, it is desirable that the soil be kept well supplied with humus materials. This is the reason for heavy manuring on the part of the truck farmer and for the use of compost and leaf mold in the growing of flowers.

FIG. 58. Liberally fertilized grassland offers opportunity for profit in livestock and milk production which is far from being fully realized. In grassland farming, erosion is stopped, expensive cultivation is eliminated, and organic-matter maintenance in the soil is no longer a problem.

INDEXES OF PRODUCTIVITY

Attempts are now being made to assign an index value to each crop and to each soil treatment in order to represent their effects on the productivity of the soil. These indexes may be either positive or negative, depending upon whether the crop or the soil treatment has soil-improving or soil-deteriorating effects. They are stated as percentage changes in the productive capacity of the soil.

Table 164 shows values which have been assigned to the several crops that are being grown in the Corn Belt states and to the several soil-management practices which are employed in that area.

TABLE 164

SOIL-PRODUCTIVITY INDEXES (SALTER)

A. Crop:	Index
Corn, as grain or silage	−2.0
Potatoes, tobacco, and sugar beets	−2.0
Oats, wheat, barley, rye, and buckwheat	−1.0
Soybeans, as hay or seed (straw not returned)	−0.5
Soybean and wheat straws, and cornstalks	+0.25
Alfalfa, for change effected by end of first hay year	+2.5
Alfalfa, for change effected during second hay year	+0.5
Alfalfa, for change effected during third hay year	0.0
Timothy and other grass sod	0.0
Clover-timothy mixed, as hay or pasture	+1.0
Common clovers, as hay or pasture	+2.0
Sweet clover, crop plowed green in April or May	+2.5
B. Soil Treatment:	
For each ton of protected manure applied	+0.15
For each 200 pounds of commercial fertilizer	+0.15

*C. Erosion Factors:**

Erosion class	Degree of erosion	No special control methods	Farmed on contour	Strip-cropped or terraced
1	Little or none	0.00	0.000	0.000
2	Slight	0.25	0.125	0.050
3	Moderate	0.50	0.330	0.125
4	Severe	1.00	0.800	0.300

* All negative values in the crop indexes are increased by an amount obtained from multiplying them by the correct erosion factor for the field or area.

Using these values, one can calculate the net effects of any system of soil management. Table 165 shows such calculations in two comparable situations.

TABLE 165

DATA SHOWING METHOD OF CALCULATING ANNUAL SOIL-PRODUCTIVITY BALANCE AS APPLIED TO TWO DIFFERENT CROP ROTATIONS (SALTER)

Situation I

Rotation: corn, wheat, timothy.
Manure applied during the rotation equals 5 tons per rotated acre.
Fertilizer applied in rotation equals 200 pounds per rotated acre.
Class 2 erosion, no special control measures.

Crop	Productivity value	
	Positive	Negative
Corn		−2.0
Wheat		−1.0
Timothy	0.0	0.0
Total	0.0	−3.0
Balance due to crop factor		−3.0
Reduction in balance for erosion (0.25 × −3.0)		−0.75
Gain in balance for manure (5 × 0.15)	+0.75	
Gain in balance for fertilizer (200 ÷ 200 × 0.15)	+0.15	
Total	+0.90	−3.75
Soil-productivity Balance:		
(a) For rotation		−2.85
(b) Annual (−2.85 ÷ 3)		−0.95

Situation II

Rotation: corn, wheat, alfalfa, alfalfa.
Manure applied during the rotation equals 10 tons per rotated acre.
Fertilizer applied in rotation equals 400 pounds per rotated acre.
Class 2 erosion, strip cropping practiced.

Crop	Productivity value	
	Positive	Negative
Corn		−2.0
Wheat		−1.0
Alfalfa (2 yr.)	+3.0	
Total	+3.0	−3.0
Balance due to crop factor	0.0	0.0
Reduction in balance for erosion (0 × −3.0)		0.0
Gain in balance for manure (10 × 0.15)	+1.50	
Gain in balance for fertilizer (400 ÷ 200 × 0.15)	+0.30	
Total	+1.80	
Soil-productivity Balance:		
(a) For rotation	+1.80	
(b) Annual (+1.80 ÷ 4)	+0.45	

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